NATIONAL RESEARCH COUNCIL

AMERICAN GEOPHYSICAL UNION

TRANSACTIONS OF 1941

PART I

JOINT REGIONAL MEETING

SOUTH PACIFIC COAST AREA
SACRAMENTO, CALIFORNIA, JANUARY, 1941

REPORTS AND PAPERS
(A) SECTION OF HYDROLOGY
(B) WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
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General Contents
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PREFACE

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

General assemblies of the Union and meetings of its Sections for presentation and discussion of papers and symposia are held in Washington, D. C., each year. The first annual meetings were those of 1920. Following the formation of the Section of Hydrology, Regional Meetings have been held usually in joint sessions with other organizations having coordinated interests. For the purpose of such meetings, the Executive Committee of the Section of Hydrology designated selected Regional Areas and their territories, namely: North Continental Divide--Montana, Idaho, eastern Washington, Oregon, and Alberta (affiliated); South Continental Divide--Colorado, Wyoming, Utah, and New Mexico; North Pacific Coast--western Washington, Oregon, Alaska, and British Columbia (affiliated); South Pacific Coast--California, Nevada, Arizona, and Hawaii. Besides the Regional Meetings sponsored by the Section of Hydrology, the Union has also encouraged joint meetings with organizations and societies interested in the discussion of various aspects of the geophysical sciences.

Thus far, Regional Meetings have been held as follows [references to publication of proceedings given refer to the "Transactions" of the American Geophysical Union, Part, and year]: South Pacific Coast Area at Berkeley, California, June 20 to 21, 1934, jointly with Western Interstate Snow-Survey Conference, June 21, 1934 [Part II, 1934, pp. 522-611 and pp. 612-633]; South Pacific Coast Area at Pasadena, California, January 31 to February 1, 1936, jointly with Western Interstate Snow-Survey Conference, January 31, 1936 [Part II, 1936, pp. 455-528 and 529-562]; South Continental Divide Area at Denver, Colorado, June 21 to 26, 1937, jointly with South Continental Divide Snow-Survey Conference, June 25-26, 1937 [Part II, 1937, pp. 509-600 and pp. 601-663, with addendum Part II, 1938, pp. 668-669], and with Society of American Foresters, June 22, 1937 [Journal of Forestry, v. 35, 1937, pp. 991-1055]; North Continental Divide Area at Spokane, Washington, December 28 to 29, 1937 [Part II, 1938, pp. 590-594]; South Pacific Coast Area at Davis, California, January 8 to 9, 1938, jointly with Western Interstate Snow-Survey Conference, January 8, 1938 [Part II, 1938, pp. 597-665 and pp. 671-744]; South Pacific Coast Area at Los Angeles, California, December 16 to 17, 1938, jointly with the Western Interstate Snow-Survey Conference [Part I, 1939, pp. 1-52 and pp. 53-96]; North Continental Divide Area at Spokane, Washington, December 28, 1938, jointly with the Western Interstate Snow-Survey Conference [Part I, 1939, pp. 97-124 and pp. 125-140]; South Pacific Coast Area at Stanford University, California, January 12 to 13, 1940, jointly with the Western Interstate Snow-Survey Conference, January 12, 1940 [Part I, 1940, pp. 1-94 and 95-144]; North Pacific Coast and North Continental Divide areas at Seattle, Washington, June 19 to 22, 1940, jointly with the Western Interstate Snow-Survey Conference and Section E of the American Association for the Advancement of Science [Part III, 1940, pp. 831-996 and 997-1062].

Joint meetings of the Union with the American Association for the Advancement of Science have also been held as follows: Richmond, Virginia, December 27, 1938, jointly with Sections D and E in a symposium on "The surface and subsurface exploration of continental borders" [Part III, 1940, pp. 781-826]; Columbus, Ohio, December 29, 1939, jointly with Sections A and E, the American Mathematical Society, the Mathematical Association of America, and the Geological Society of America in two symposia, namely, "Applications of mathematics in the Earth-sciences" and "Hydrologic problems in the Ohio and Michigan basins" [Part IV, 1940, pp. 1063-1146].

Part I of the present volume, "Transactions of 1941," contains the papers and discussions at the Regional Meeting of the South Pacific Coast Area at Sacramento, California, January 16 to 18, 1941, jointly with the Western Interstate Snow-Survey Conference, January 16, 1941.

The officers of the Section of Hydrology, and the officers and members of Committees of th Regional Areas and of the Executive Committee of the Western Interstate Snow-Survey Conference are as follows:

Section of Hydrology, American Geophysical Union

N. C. Grover, President M. P. O'Brien, Vice-President K. H. Beij, Secretary

South Pacific Coast Area

Chairman, F. J. Veihmeyer Local Chairman, Harold Conkling

H. F. Blaney
J. E. Church
Harold Conkling
C. E. Elder
S. T. Harding

M. R. Huberty
Charles J. Kraebel
D. Arnold Lane
Charles H. Lee
Samuel B. Morris

M. P. O'Brien
Fred S. Scobey
Franklin Thomas
F. J. Veihmeyer
Baldwin M. Woods

Executive Committee, South Pacific Coast Area
Western Interstate Snow-Survey Conference

Fred H. Paget, Chairman Secretary for Meeting, Olga Austin

H. P. Boardman James E. Jones Joseph Kittredge, Jr. William A. Lang

The costs of publication for the transactions of the Regional Meeting of the Section of Hydrology were provided by the American Geophysical Union. Those for the proceedings of the Snow-Survey Conference were contributed by interested organizations and individuals and by the American Geophysical Union. Assembly and preliminary editing of the manuscripts of the Section of Hydrology were made by Harold Conkling and of the manuscripts of the Snow-Survey Conference by Fred H. Paget with assistance from Dr. J. E. Church. Final editing and preparation of master-copy for publication were done by Dr. J. A. Fleming and J. J. Capello, General Secretary and Assistant Secretary, respectively, of the American Geophysical Union, and by W. E. Scott. We are indebted to W. C. Hendrix for the necessary redrawing of figures and photographic work for publication.

The content and discussion of the investigations reported upon in the papers before the Section of Hydrology and the Western Interstate Snow-Survey Conference at Sacramento furnish abundant evidence of the ever-increasing value of the scientific and economic aspects of geophysics.

J. A. Fleming, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

REGIONAL MEETING

SOUTH PACIFIC COAST AREA

January 16-18, 1941

PART I-A

SECTION OF HYDROLOGY

REPORTS AND PAPERS

Sacramento, California

January 16, 17, 1941

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SESSION, MORNING OF JANUARY 16, 1941--MEMORIAL AUDITORIUM
CHAIRMAN, M. P. O'BRIEN

INTRODUCTORY DISCUSSION AND COMMENTS ON THE THREE PAPERS BY HYDE FORBES, IRVIN M. INGERSON, AND WALTER WEIR

S. T. Harding

These three excellent papers present the ground-water conditions and problems of the San Joaquin Valley from three different points of view. Taken together they comprise a very good picture of the ground-water resources of the Valley. As the water-supply problems of the San Joaquin Valley are more acute in the portion of the Valley south of Chowchilla River it is natural that the authors devote more of their discussion to this portion. This should not cause us to lose sight of the fact that a large part of the best development in the Valley is in its northern part where nature has been more liberal in providing an adequate water-supply.

In discussing papers by others it is a natural tendency to comment mainly on those points made by the authors with which the discusser is not in agreement. Discussion of items on which there is agreement is more largely repetition of the author's paper. I have followed this tendency in my discussion but this should not be considered to be a criticism of the papers as a whole. The entire subject of the ground-water of the San Joaquin Valley is so large and involved that full agreement on all of its details is not to be expected.

Mr. Forbes presents a very good history of the geology of the Valley. Such a history is necessary in the understanding of the ground-water conditions. The tendency to drill deeper in an effort to tap additional water-strata increases the importance of the geology of the Valley in relation to its ground-water supply. The great majority of the past wells and most of the recent irrigation wells are in recent alluvial materials. It is a very fortunate condition that in large parts of the east side of the Valley almost any well is reasonably certain to encounter fairly good water-bearing material at feasible depth although the details of the depth and thickness of such strata vary in adjacent wells. In those areas of more active recharge this condition is generally true. This is to be expected as such areas are the ones where greater amounts of recent alluvium have been deposited. This condition applies to the deltas of the present tributary streams of the Valley. As the streams having material amounts of runoff are limited to the east side of the Valley the main ground-water supplies are also so limited.

Mr. Forbes refers to the faulting in the trough of the San Joaquin Valley. It is reasonable to assume that the extensive past geological movements in the Valley include faulting along specific shear-lines. The question in relation to the ground-water conditions of the Valley is whether such faulting has occurred sufficiently recently to affect ground-water conditions within the depths of the Valley fill from which ground-water is being drawn.

Faults are of various kinds. They occur in some California areas as definite surface-scarps and result in a material break in the continuity of water-bearing materials. Such faults do not occur on the floor of the San Joaquin Valley. Any fault that may exist in the Valley fill is buried at sufficient depth so that recent deposits cover it on both sides. The ground-water contour-maps shown by Mr. Ingerson do not indicate any break in the ground-water elevations across the fault-line described by Mr. Forbes. I have been unable to find indications of any such faulting within the depths of wells now in use in the work I have done in this area.

There is a natural gradation of material from the Valley sides toward the center, the coarser debris being deposited at the edges. Beyond the outer edges of the deltas of the present streams, water-bearing materials are finer and good yields require greater depths of water-bearing strata. This condition occurs across the line described by Mr. Forbes as a fault. There was no break in the ground-water contours across this line for either the surface or the artesian strata as they existed prior to the lowering of recent years. There were no such breaks indicated in earlier well-logs although such logs frequently lacked desired detail and definiteness. The differences in quality of the ground-waters described by Mr. Forbes do not demonstrate the existence of such a fault as such differences occur vertically as well as horizontally. In some west side areas the deeper ground-waters are more nearly of the east-side type than the waters encountered in the shallower strata.

Mr. Ingerson describes the observational program that has been in progress for over 20 years

and the methods used in the analysis of the results. These areas present an unusually favorable opportunity to study supply and draft. Inflow occurs almost wholly in measurable surface-streams. Rainfall on the Valley floor is too small to result in any material rainfall-penetration to the ground-water. Ground-water movement between the areas receiving separate sources of inflow is so slow under the flat slopes that occur here that general ground-water inflow or outflow are also relatively small. This latter condition has become painfully apparent where extensive pumping has been undertaken in areas distant from active sources of recharge. Large amounts of ground-water storage occurred in such areas as the result of long periods of accumulation. The pumping of such supplies has depleted some of these areas much as mineral areas are depleted by similar extractions.

Mr. Ingerson emphasizes the need of studying conditions by separate areas and points out the uselessness of discussing Valley averages. With this I am in full agreement. Ground-water conditions in this area run the full scale from feast to famine and the average has no value to an individual area. I would go even further than Mr. Ingerson in breaking down the areas separately considered. The Tule-Deer Creek Area which he used as an illustration includes a small area near Tule River which may have an adequate natural recharge and some areas of very limited supply. While the resulting deficiency for the whole area should be correct in terms of the total amount of outside water needed, further detail breaking down of that deficiency to smaller local areas will be required in the purchase of additional water and in plans for its delivery so as to meet present shortages.

Mr. Weir expresses the view held by many engineers regarding the drainage of irrigated lands. Engineers have seen lack of drainage injure much land and have a better long-range perspective than the average irrigator. Consequently engineers are usually ahead of the landowners in their plans for remedial works. There is a need for more understanding between both groups for the better working out of these problems. There is a general feeling among landowners in many areas that ground-water does not need to be lowered as deeply as many engineers desire. Neither group has sold their point of view as yet to the other. There is a field here where a more complete exchange of information by both sides should be helpful. Drainage has to be "sold" to the landowners before they will finance its costs. Mr. Weir's illustrations indicate that it has not been sold as yet in some areas. Progress is being made, however.

I do not share Mr. Weir's concern over additional need for drainage resulting from the use of water from the Central Valley Project. Past development in the San Joaquin Valley where surface-stream supplies have been used has consisted of generally relatively low-cost canal systems with ample water during at least part of the season. Excessive use under such conditions has generally resulted. This condition will not occur under the Central Valley Project. If the lands served have to meet the necessary costs of this project no areas can afford to buy enough water to water-log themselves. Half of the Central Valley Project water will be of irregular occurrence useful largely for ground-water recharge and requiring continued dependence on at least partial ground-water pumping. Accumulation of supplies sufficient to result in water-logging is not probable under these conditions.

These three papers illustrate why the San Joaquin Valley is such an intriguing area to those interested in hydrology as well as those having less technical interests in the development of irrigation. It represents an immense and an immediate problem in both the preservation of parts of the present irrigation and in the development of additional areas. It involves matters of public policy with which everyone is concerned. On the more technical side of its hydrology the present rates of draft result in such rapid changes that it represents the equivalent of an accelerated experiment where the effects which would require years to become apparent in many areas take place before our eyes as we make the investigations. The Valley has met the past problems that have arisen in the course of its development and we can look forward with confidence that it will meet its present and future problems. All three authors deserve our thanks for their contributions to our understanding of the hydrology of the Valley.

University of California,
Berkeley, California

GEOLOGY OF THE SAN JOAQUIN VALLEY AS RELATED TO THE SOURCE AND THE OCCURRENCE OF THE GROUND-WATER SUPPLY

Hyde Forbes

General--The San Joaquin Valley is that portion of the great Central Valley of California lying south of the Mokelumne River and the Delta of the San Joaquin River, rising in elevation

from sea-level at Suisun Bay to about 1,000 feet above sea-level at its southerly border.

General geology--The geologic history of the Sierra Nevada and Coast Ranges is determined from the formations exposed over their surfaces and the geologic structure of the mountain blocks. That of the Valley lying between is deduced therefrom as the geologic formations of the mountains are buried beneath later or younger sediments in the Valley. The exact knowledge of subsurface conditions is limited to that revealed through the drilling of water-wells, the static and pumping water-levels of these wells, the chemical character of their waters, and in petroleum exploration and well-drilling.

In general, the great central valley of California has been a depression, sinking as the bordering mountain ranges have risen, into which the streams have carried the sediments derived through the wearing down of the mountains and over which these sediments have been spread.

Geologic history--The Sierra Nevada Range was formed by the intrusion of great masses of granitic rock into and beneath thicknesses of sedimentary beds in Jurassic geologic time. The result was the uplift of the Sierra Nevada region forming a mountain barrier between the Great Basin and the Pacific Ocean

The pre-existing sedimentary beds were thrust up and around the igneous magmas in complex folds. The great pressures exerted and the heat and gases from the molten-rock masses caused the fine silts, sand, and gravel sedimentary formations, and the lava and tuff which were formed by volcanic action contemporaneous with the laying down or consolidation of the sediments, to become hardened, recrystallized, and changed to what is now known as the Sierra Nevada metamorphic bed-rock complex.

Limited areas of the Earth's crust over the region now occupied by the Coast Range were subjected to intrusion and were forced upwards to exist as islands in the Cretaceous sea. During Cretaceous geologic time the Sierra Nevada mountains and the islands were worn down through stream-erosion and the fragmental rock so derived was carried by the streams into the sea and deposited.

At that time the Sierra Nevada Range was low, probably not reaching an altitude of more than 6,000 feet above the sea which flanked its slope and extended westerly to meet what is now the Pacific Ocean. The enclosure of the central valley, except at its southern end, was accomplished at the close of Cretaceous time by the folding and uplifting resulting in the Coast Ranges. The sediments and siliceous ooze laid down in the Cretaceous sea were subjected to compression, brought above sea-level, and consolidated into rock. These formations are lacking in Sierra Nevada exposures but make up great areas, principally in the form of shale, over the Coast Ranges.

Contemporaneous with this mountain-making movement the valley-region was further depressed and occupied by the Tertiary sea. The Tertiary shore-line therefore came further east along the west flank of the Sierra Nevada. Several minor crustal movements were experienced by the region in Tertiary geologic time with a corresponding fluctuation of the shore-line.

The Sierra Nevada was further worn down through erosion. The tops of the folded sediments were removed and the land-surface was carried down into the heart of the original range to expose the intrusive granite which had cooled thousands of feet below the surface. The Coast Range also suffered erosion adding its sediment to that from the Sierras to be spread over the bottom of the Tertiary sea.

The Sierra land-surface was brought to low relief but not to a plain as the present more prominent peaks stood well above the general level and there existed wide stream-channels between rock-slopes. The sediments deposited by the Sierra streams in their channels are those now found at elevations high above the modern stream-channels and known as the Tertiary gold-bearing gravels.

San Joaquin Valley sediments--The sediments carried into and along the border of the gulf-like San Joaquin Valley depression during Tertiary time consist, in their upper thicknesses, of the fine-grained tuffs, sands, and clay and coal beds, loosely consolidated, now exposed along the northerly portion of its east border between the Mokelumne and Tuolumne rivers, and the sands, conglomerate and clay-shale beds flanking the more southerly slopes of the Sierra Nevada to the Tehachapi Mountains. Similar materials make up the greater surface-area of the Tehachapi and the east slope of the Coast Range Mountains.

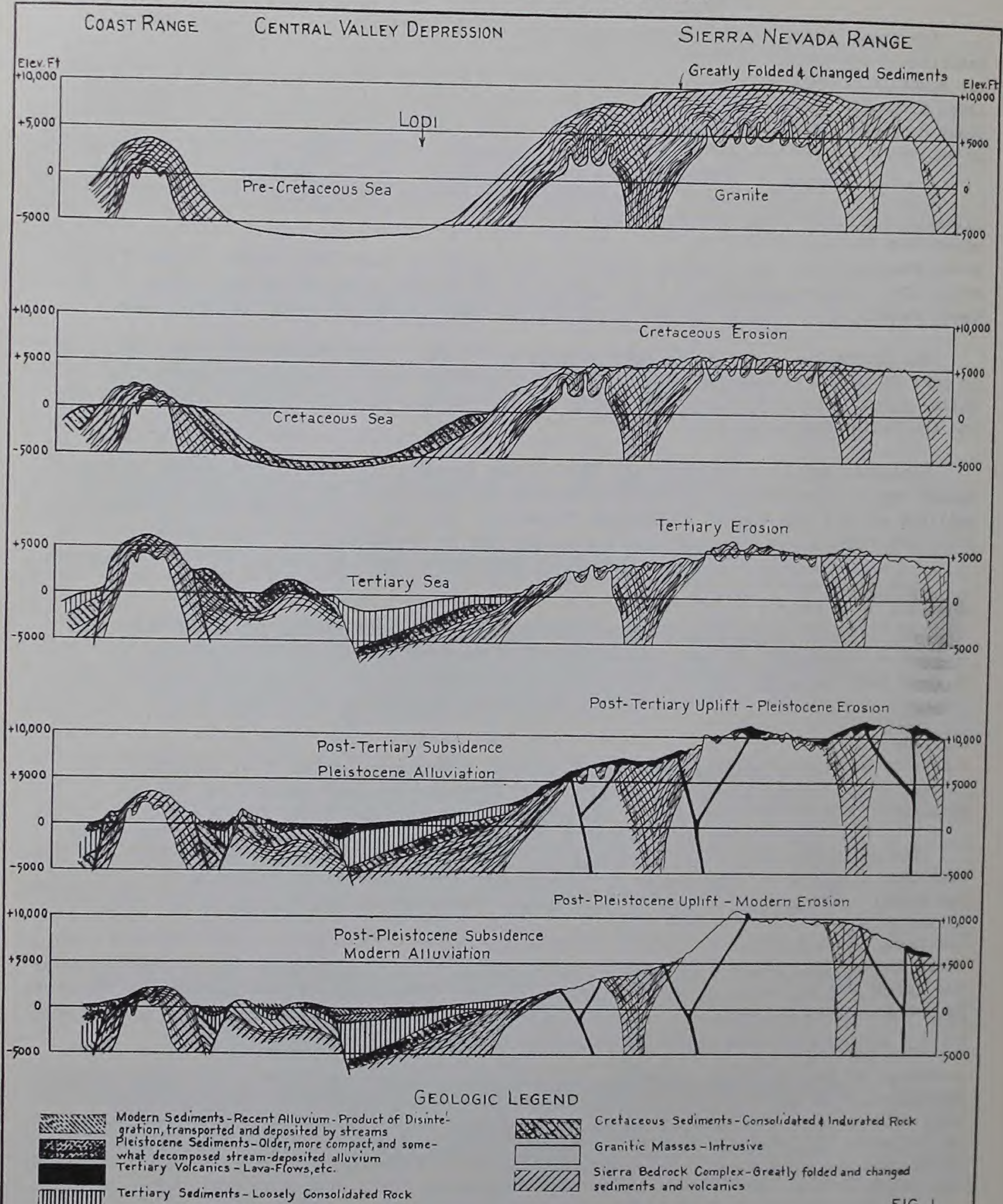


FIG. 1

Judging from these exposures, there lies at depth in the San Joaquin Valley a sequence of sediments consisting of tuffs, pumiceous conglomerates, loosely cemented sandstone, siltstone, and claystone or shale. Outcrops of these formations are found exposed in river banks extending, in places, as much as one-third of the distance from the older Sierra Nevada Range rocks towards the trough of the Valley. They appear in cores recovered in petroleum exploration to depths in excess of 5,000 feet.

The Tertiary period of sedimentation was brought to a close by a period of active volcanism which produced the great lava- and ash-fields of Northern California and the lava-, breccia-, and mud-flows which passed down the Sierra slopes filling canyons and capping existing stream-channels and extending, in places, into the Valley over which clouds of volcanic ash were carried to be deposited as tuff during this period.

The great period of intense volcanic eruption was accompanied by crustal adjustment which resulted in the uplift of the Sierra Nevada Range to near its present altitude and a tilting of the mountain block to the southwest. This movement carried the Tertiary sediments above sea-level along the west flank of the Sierra Nevada. Intensive folding and faulting throughout the Coast Range and Tehachapi regions resulted in their uplift, which formed mountain chains entirely enclosing the San Joaquin Valley.

This great mountain-making epoch brought about the rejuvenation of drainage along new lines. Climatic conditions were cold and humid, great glaciers formed south from the Arctic regions and moved from the high Sierra regions to lower levels. As the climate tended towards the arid the great snow-packs and ice of these glaciers melted. The resultant quantities and swift flow of water from the mountains deeply eroded the watershed-areas and the Tertiary sediments along their borders.

The sediments so derived during Pleistocene time were deposited in the Valley depression, in part in great fresh-water lake bodies and, as these became filled, as great stream-fans and a valley plain. The movement of all this water from land-surfaces raised the level of the sea and the Valley was inundated at its lower level.

Continued uplift of the mountain ranges since Pleistocene time has caused a warping of the Valley region in adjustment. The Pleistocene or older alluvium is found as great alluvial fans, uplifted and dipping slightly towards the Valley from the east, folded and faulted in the Lost Hills-Kettleman Hills chain, and plunging steeply from the west beneath the younger alluvium.

Throughout Recent geologic time the San Joaquin Valley has been a depression, the trough of which has been sinking as the bordering mountain ranges have been rising, into which the streams from the bordering watershed-areas have carried and dropped recent sediments. The Pleistocene or older alluvial fans have been eroded by the major streams which laid them down and dissected by minor runoff.

Physiographic units related to ground-water occurrence--There have been developed through faulting and recent erosion and deposition certain geological features and physiographic distinctions which are largely controlling in the occurrence of ground-water in the San Joaquin Valley, and in the distribution of types of surface and sub-soil involved in ground-water replenishment and economic recovery.

The geological features are those of structure which affect the deep ground-water. These have been established, possibly with some indefiniteness, through the ground-water studies of the author. The principal feature is a major fault extending, buried beneath alluvium, from one of the northwest-southeast faults (possibly the Poso Creek Fault) northerly in the vicinity of Corcoran, Mendota, Tracy, along the east base of the Montezuma Hills to enter the Coast Range at Cache Creek. This block-displacement consists of a downthrow on the west at the southern end of the Valley and on the east at the northern end, with both blocks rising to the north, the depth to marine sediments below the alluvial surface becoming increasingly greater to the south.

The physiographic units may be divided into (1) the low mountainous or foothill area encircling the Valley, (2) an uplands area on the east of "older" alluvium, (3) a border area of geologically recent thin alluvial "veneer" overlying older formations, (4) the geologically recent alluvial fans and flood-plains of the major Sierra streams and Orestimba and Puerto creeks on the west, (5) the river-bottom and terrace-borders of the tributaries of the San Joaquin River, and (6) the reclaimed swamp and overflow-lands of the Buena Vista and Tulare Lake basins, the Valley Trough, and the islands of the delta-region.

The low mountainous or foothill area encircling the Valley is made up of Tertiary rock-formations. Erosion has produced a dissected table-land, some of the more westerly tables being covered with a resistant volcanic breccia-capping or remnants of the heavy gravel-and-boulder Pleistocene deltas of the major Sierra streams. The coarser sand-beds of the upper Tertiary formations are found to yield water in the foothill areas where rainfall upon or stream-flow over surface-exposures has supplied water to penetrate into the porous beds. The well-supplies are small and water-levels in wells are erratic in that there is no continuous uniform water-table evidenced.

The fine-grained clay-shale and tuff-beds of the formations are practically impervious, so that, beyond the area of surface-exposure where the formations dip deeply beneath the Valley floor, the water contained in the coarser members and reached by deep wells is not that supplied by vertical percolation from overlying water-bearing formations. These Tertiary beds are in

FIG. 2 (A)

part marine, in part lacustrine or lake in origin, and in part alluvial. The water they contain is highly mineralized or marine salt water entrapped in the formation as it was laid down. Consequently, the Teritary formations can be considered bed-rock in the San Joaquin Valley in relation to the economic recovery of potable water.

The uplands areas of older alluvium consist of deposits which can be characterized as a heterogeneous mass of fragmental rock-material, containing limited lenses of well-assorted sand

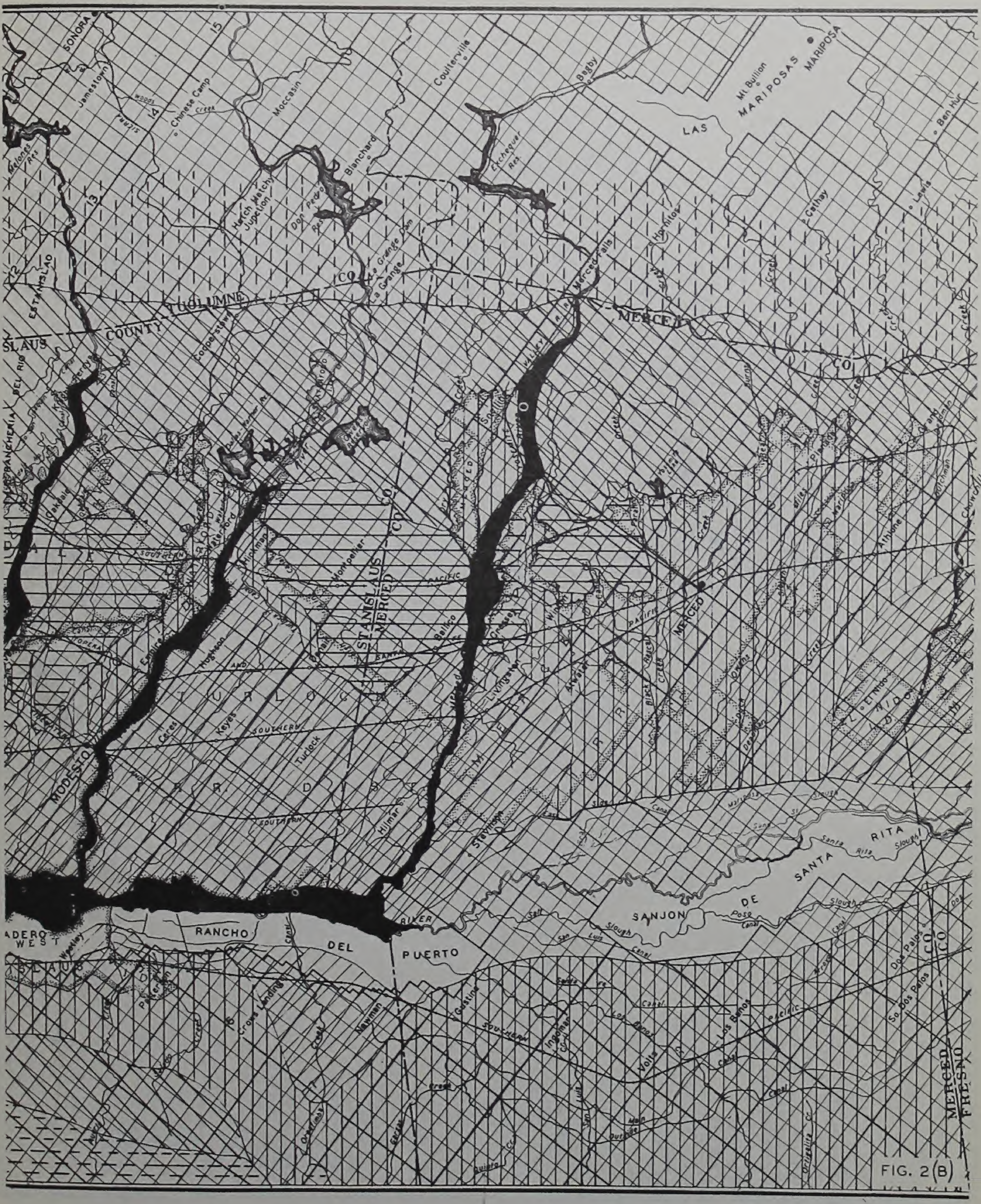


FIG. 2(B)

and gravel laid down as stream-channels. These channels were abandoned by the stream and their depressions were grown over by vegetation and filled with fine wind-blown material. They were cut at intervals throughout their lengths by subsequent surface-stream erosion in the establishment of new channels and are thus left as lenticular bodies of sand and gravel imbedded in a matrix of finer or poorly assorted material.

Sections of the deposit or formation, as exposed in river-banks, road-cuts, and other ex-

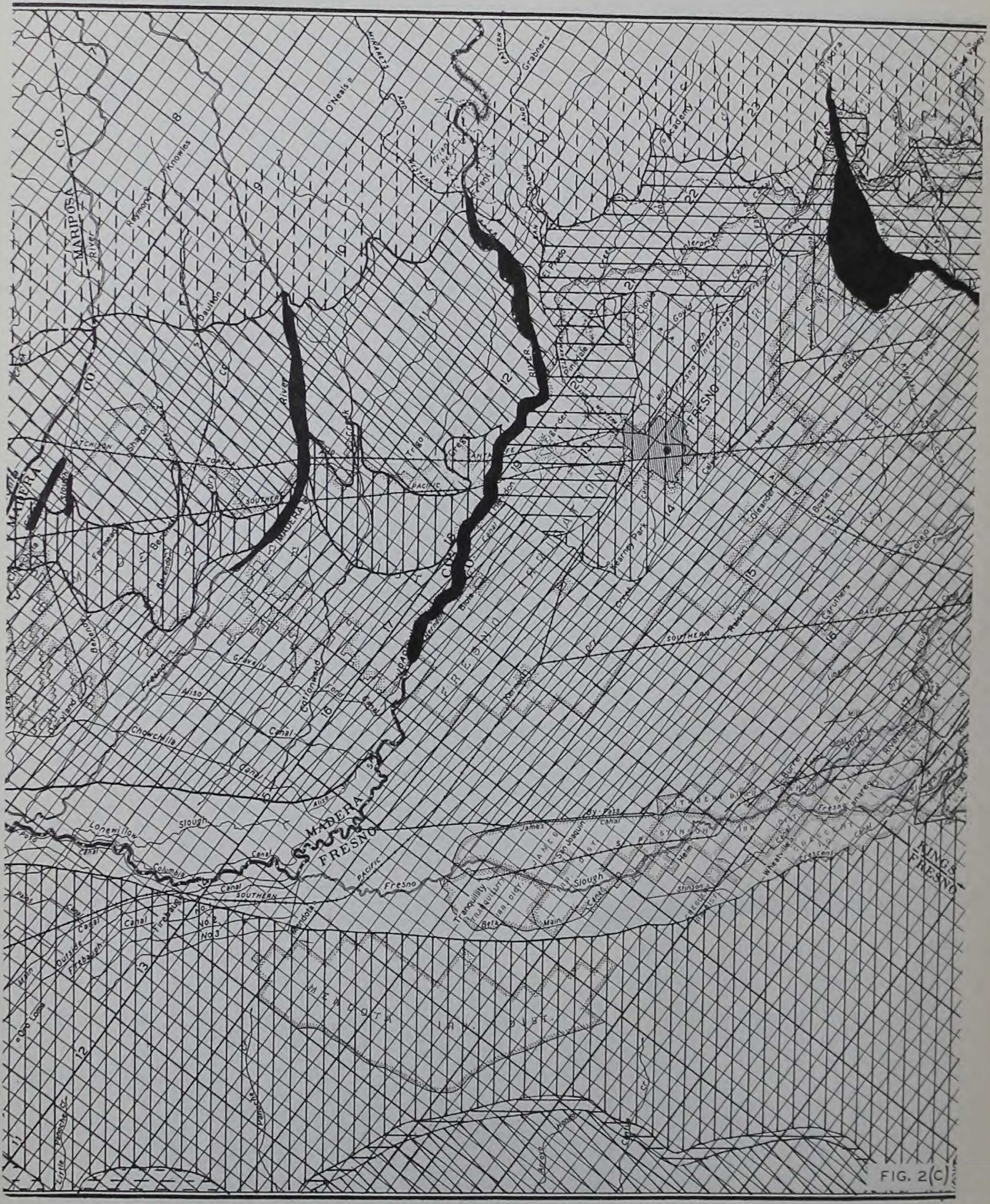


FIG. 2(C)

cavations, show no continuity of materials of like texture or grain-size, but rather a chaotic mass in which fairly well-defined lenticular bodies of gravel and sand will give way abruptly to bodies of finer material. All the materials making up the deposit were originally porous and permeable, the degree of porosity and permeability now varying widely throughout the deposited materials. This is in part due to the compaction of weak finer sediments under the overlying loads and in part due to the breakdown of some of the constituent minerals, forming soluble salts to be dissolved by the water passing through the formation and reprecipitated in the in-

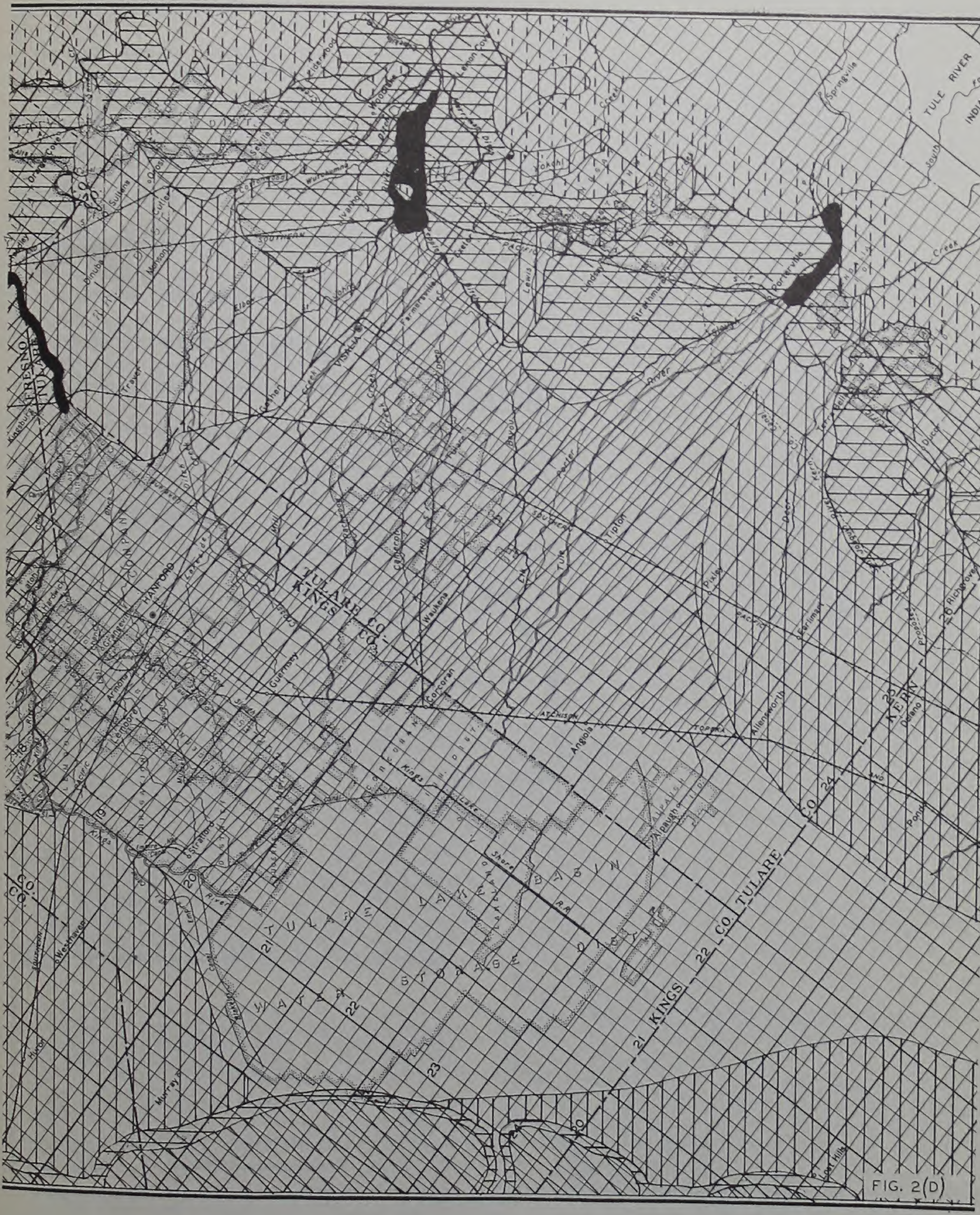


FIG. 2(D)

terstices.

The decomposition or oxidation of the ferromagnesium minerals in the older alluvium has provided the iron oxide which gives it the characteristic red color and acts, with calcium carbonate and soluble silicates, as a cementing material resulting in the formation of "iron hardpan" in the upper thicknesses. The red color of the present surface-soil of the older alluvium distinguishes it from the younger alluvium, but in drilling samples the differentiation is dif-

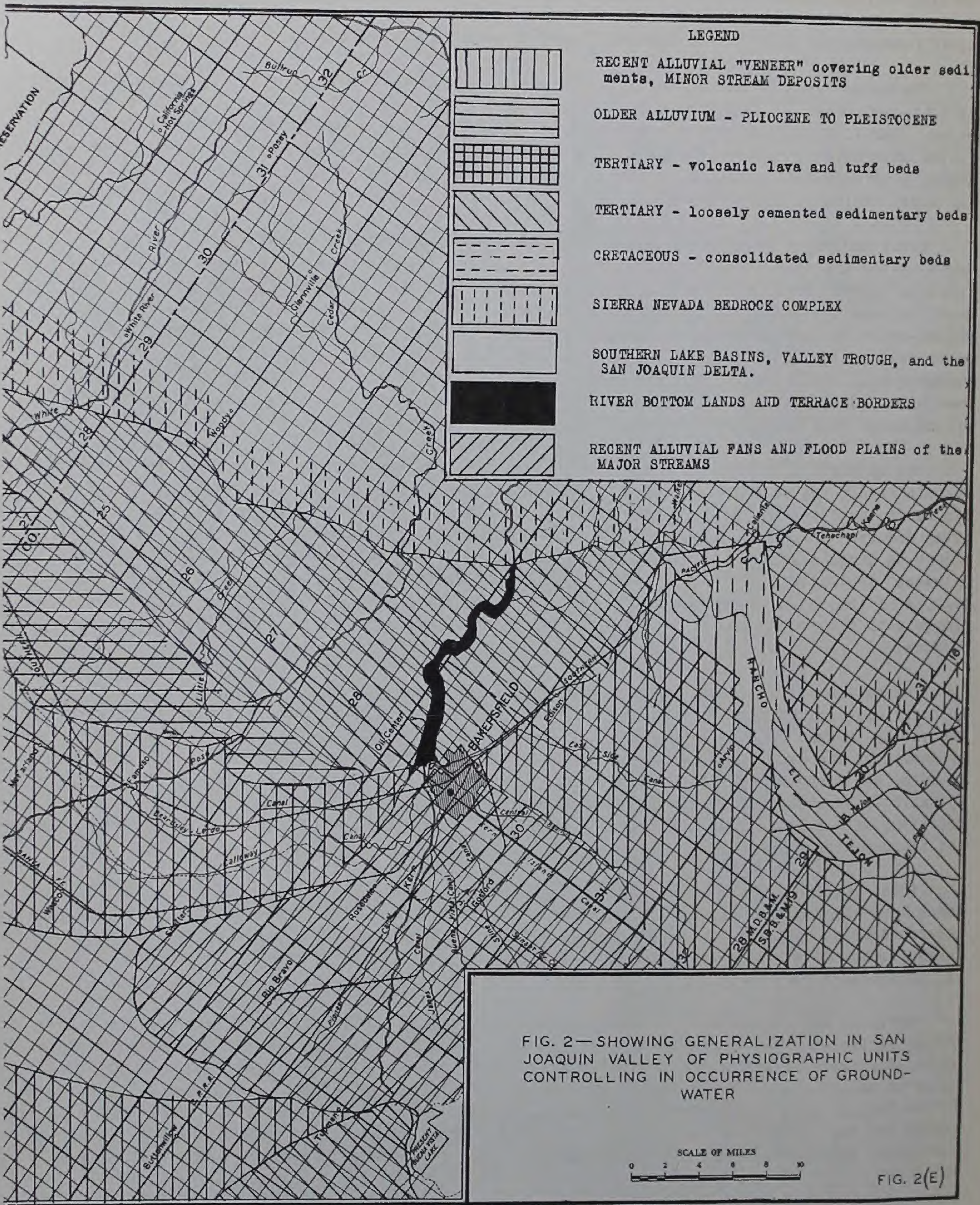


FIG. 2—SHOWING GENERALIZATION IN SAN JOAQUIN VALLEY OF PHYSIOGRAPHIC UNITS CONTROLLING IN OCCURRENCE OF GROUND-WATER

ficult because both were laid down by the same agencies in the same manner and both produce sands consisting of quartz-grains with unaltered fragments of feldspar, flakes of mica and hornblende, and magnetite.

The development of drainage-patterns over the older alluvium in contrast to the relatively plain surface of the younger alluvium is indicative of the induration that has taken place in the former. Much of the rainfall upon its surface is shed. Wherein ground-water circulation

through certain gravel- and sand-members has carried on oxidation and cementation, these processes have sealed otherwise good acquifers. As a whole, the formation is not one which absorbs water readily, nor does it yield water freely to wells in large quantities.

The border area of geologically recent alluvial "veneer", overlying the older alluvium and Tertiary sediments in certain areas, is the result of the dissection of the uplifted older sediments. Runoff-erosion of the formation has produced fine-textured alluvial material which has filled depressions produced by the earlier erosive development, filled the stream-trenches of the lesser Sierra foothill-creek drainage-systems, and has produced a cover of finer sediments over the older sediments along the border of the modern flood-plains of the major Sierra rivers.

These sediments provide ground-water storage-areas of limited extent, laterally and to depth, which are charged with water derived from minor runoff and contain their ground-water "perched" above the underlying indurated older sediments and, while the latter receives some contributions therefrom, the rate of transmission of the water to depth is so slow that the ground-water of such areas is not to be considered part of the general ground-water body. The water reached in dug pits lies at a higher elevation than the water-level in nearby bored wells reaching into the older sediments. Particularly is this true of the larger creek-channels which have been filled with material acting as ground-water reservoirs "perched" above the general ground-water body.

The geologically recent alluvial fans and flood-plains of the major tributaries of the San Joaquin River, the rivers and larger creeks of the Tulare Lake Basin, and Los Gatos, Orestimba, and Puerto creeks from the west comprise the younger alluvium lying between the "red-land" areas and the San Joaquin Valley trough. It consists of a uniform and permeable fill capable of absorbing large quantities of water and freely transmitting it from place to place and vertically except in the valley-trough areas. It comprises an extensive underground reservoir which, because of its intimate association with the streams which laid it down, is subject to ready recharge with the occurrence of flood-discharge in the streams and from water spread over its surface.

The action of the Sierra streams after the Pleistocene period consisted of eroding trenches in their older alluvial fans in achieving a new base-level in adjustment with the depression of the valley-trough. The earlier courses of the streams were more southerly than the present, as evidenced by the broad terraces bordering the present entrenched channels of the Mokelumne, San Joaquin, and Kings rivers. As aggradation of the Valley continued the tendency of the rivers was to shift to more northerly courses, cutting more deeply into and removing its older alluvium and refilling with sediments as the gradient flattened in deepening and widening their alluvial fans and flood-plains.

Those portions of the valley-trough occupied by the beds of Kern, Buena Vista, and Tulare lakes were the residual basins for water originating in the Sierra, Tehachapi, and Coast Range watershed-areas south of the Kings River-Los Gatos Creek Divide. The surface-areas of these lakes fluctuated widely from season to season but, in the course of the alluviation of the valley-trough a very considerable thickness of lacustrine deposits were laid down.

North of the Kings River-Los Gatos Creek Divide the physiographic conditions of the valley-trough varied with the occurrence of wet and dry cycles. During the wet cycles extensive fresh-water lakes were formed which in dry cycles were partially drained and their lower levels reduced to swamps. The fine sediments carried to these lake-bodies were spread over their bottoms in the form of more or less continuous silt- and clay-beds. With continuing trend of the climate toward the semi-arid, the lakes became dry, stream-deposits were laid down over higher lying lake-beds, wind-blown sands were carried to the area and a broad swamp and overflow-plain was built up.

The clay-beds, which mark the old lake-bottoms, lie at varying depths below the San Joaquin Valley trough areas from south to north. They are penetrated by the deeper wells and, while not constituting as wide-spread, unbroken blanket at one level north of the Kings River-Los Gatos Creek Divide as in the lake-basins to the south, they are extensive and continuous in comparison with the lenticular bodies of clay of the stream-fans. These clay-beds resist the downward and upward movement of water so completely that, for all practical purposes, the shingle-like structure separates the ground-water of the lake-bottom and trough-areas into horizons, in contrast to the great bodies of ground-water in contact throughout in the stream-fans.

The fault which the trough of the Valley follows has a marked effect upon the ground-water of the San Joaquin Valley. The water draining from the Sierra Nevada rock-formations is rela-

tively free from soluble salts. The principal chemical constituents of the ground-water east of the fault are bicarbonates, which are derived through the leaching of the soil by percolating water originating as applied irrigation-water and seepage from canals to a large extent. The major portion of the rock-formations making up the Coast Range watershed-areas are sedimentary beds containing considerable gypsum. Consequently the soils on the west side of the San Joaquin Valley derived from them contain gypsum, are generally "hard" with large areas characterized by hard-pan subsoil, and adobe soils have developed at lower elevations. The solution of the gypsum in the soil by the percolating water accounts for the high sulphate content of the west side underground and drainage water.

The fault acts as an underground barrier preventing the commingling of the east-side (bicarbonate) and west-side (sulphate) ground-water at depth. The irrigation-water of the systems serving the lands of the Orestimba and Puerto Creek fans, however, is derived from the San Joaquin River which, after the month of June in most years, is made up largely of return flow of ground-water from the east-side areas to the channel upstream from the points of west-side surface-diversions. As a consequence, the soils of these areas have been leached, are more open to water-penetration, and their ground-water is a composite with the sulphate content lowered in percentage.

The river bottom-land and terrace borders of the San Joaquin River and its tributaries are the result of physiographic development during the latest period of geologic time. These streams have been entrenching themselves in their recent alluvial flood-plains, below which the streams have now cut their channels, forming alluvial bottoms and bordering terraces. The terraces developed, for the most part, are low and subject to overflow in extreme flood-periods of flow. Except for a silt top-soil their characteristics are those of the river-bottoms and they are continuous with the porous material of the existing stream-channels. These open materials are almost immediately charged with ground-water from and to the level of the flood-flows in the streams.

The effect of stream-entrenchment has been to deprive that portion of its original flood-plain deposit lying above the river-surface of its ground-water charge and limited the underground reservoir to that portion lying below the river water-surface. Except in the Mokelumne Area where irrigation is had through pumping of wells, the entrenched river-channels north of the Tulare Lake Basin act as drains for the ground-water bodies built up through irrigation-activity over their adjoining plains.

The reclaimed swamp and overflow-lands of the Buena Vista, Kern, and Tulare Lake basins, the valley-trough, and the islands of the delta-region are modifications due to man which, with spreading of surface-water in irrigation and pumping draft, are the important factors in the present-day ground-water conditions of the San Joaquin Valley. Irrigation-applications and canal seepage augment ground-water storage, raising the water-table closer to ground-surface. The drainage-facilities provided in these irrigated areas lower the water-table during the non-irrigation period and tend to restrict the ground-water rise during the entire year. Pumping draft from ground-water for purposes of irrigation have greatly modified ground-water conditions causing a lowering of water-table levels over the Mokelumne Area and considerable areas in the Tulare Lake Basin.

In a state of nature, the southern lake-basins and the trough of the San Joaquin Valley were the residual basins to receive surface- and ground-waters from the east and west tributary drainage. The construction of protective levees along the lower channels of the major streams, in the lake basins or bottoms, and along the San Joaquin trunk-drainage through the valley-trough, keeps the flood-water from spreading over these former swamp and overflow-lands and confines surface-flow to fixed channels except in time of extreme flood. Consequently, the major river-channels have been eroded deeper and now act as ground-water drains through the greater portion of each year and as surface-water carriers during periods of winter storms and during the melting of the Sierra snow-pack in the spring and early summer months.

Consulting Engineering Geologist,
San Francisco, California

DISCUSSION

HYDE FORBES--The question raised by Mr. Harding in relation to the San Joaquin Valley Fault is "whether such faulting has occurred sufficiently recently to affect ground-water conditions within the depths of the Valley fill from which ground-water is being drawn." In reply it can

be stated that the San Joaquin Valley Fault is a dominant structural feature approximately parallel to the San Andreas Fault and separated from the latter by the Diablo Range. The areas to the east, west, and southwest of the Fault exhibit distinct types of geologic structure, that to the east being the monoclinal Sierra Nevada province in contrast to the folded and faulted Coast Range-Tehachapi province.

Geophysical exploration and the correlation of the stratigraphic records of oil-wells indicate that pronounced movements have taken place since mid-Tertiary time. Records of earthquake-shock indicate continuous movement through the present. Present movements may be largely horizontal, as indicated by the offset and cross-faulting and the movement of 1906 along the San Andreas accounting for the lack of definite surface-scarps, but large vertical displacements have taken place in the past and vertical displacement is now occurring along the northerly end as evidenced by the occurrence of fresh-water peat-beds at 90 feet below sea-level west of Lodi.

The effect of the Fault upon ground-water conditions varies, of course, with the induration of materials through which it passes and the amount of movement causing unlike materials to abut against each other. During the years 1917 through 1922 the water-levels in a large number of wells on the lower Cross Creek, Elk Bayou, and Tule River deltas were observed in connection with a water-rights litigation. The greater number of these wells were of shallow depth, ending in the recent sediments laid down by those streams. The water-table determined therefrom was a continuous plane surface. That is to be expected as faulting, in Southern California as well as the San Joaquin Valley, through uniform open recent alluvium has little effect upon ground-water levels. However, the water-levels in deep wells showed a definite break. Such wells were not numerous at that time but sufficient existed between Angiola and Hanford to prompt a study of the condition and corroborative evidence was collected in the nature of logs from deep gas-wells and the location of a line of gas "blow-holes" in the sediments as the water of Tulare Lake receded.

In 1926 and 1927 an opportunity was afforded to study the water-levels, well-logs, and chemical analyses of well-waters covering the Tulare Lake Basin and west-side wells to north of the Los Gatos Creek-Kings River Divide. At that time a large number of deep wells had been drilled in the area, penetrating to as deep as 2,600 feet. Some of the wells reached and drew water from marine sediments and most of them drew from the Tulare Formation, composed of loosely consolidated sands, clays, and gravel deposited as fresh-water lake-beds and subaerially. This formation corresponds in age to the older alluvium of the east side and has suffered marked deformation in the Kettleman Hills-Coalinga Area and at the mouth of Cache Creek in the Sacramento Valley.

The information so obtained allowed the approximate location of the Fault through the area and work done in 1930 south of Angiola provided data for its southern extension. Recent work done by a major oil-company with torsion-balance has checked the approximate location of the Fault as determined through water-levels in wells. A collection of newspaper reports of earthquake-shocks reported from Hanford, Corcoran, Fresno, and other points in the Valley and the reports of the United States Coast and Geodetic Survey attest to the activity of the Fault. The northerly extension of the fault-trace is more difficult as it passes through the recent alluvial deposits of Kings River and the San Joaquin River. The deep wells, their artesian water-levels, and the chemical character of their waters, as far north as Crow's Landing observed during a study made in 1932 and 1933 covering the trough-area of the San Joaquin Valley, allow the approximate location of its trace.

In reference to the differences in the quality of the ground-waters occurring vertically as well as horizontally mentioned by Mr. Harding, that is true but it has nothing to do with the occurrence of the Fault. These differences are differences in chemical constituents due entirely to the formation drawn upon. The Tulare Formation of the Tulare Lake Basin and the older alluvium of the east side contain water of similar character carrying in solution bicarbonates derived through the chemical breakdown and leaching of the unstable minerals it contains. The overlying alluvium of the Los Gatos Creek and other west-side creek-fans to depths of as much as 400 feet contain water high in sulphate derived from gypsum in their sediments. The ground-water of the same or lesser depths in the recent alluvium of the areas of the Kern, Tule, Kaweah, Kings, and San Joaquin rivers is relatively free from mineralization as sufficient time has not elapsed for decomposition to have taken place. The very deep wells, and moderately deep wells of the Lindsay-Strathmore and other foothill districts of the east side, penetrate Tertiary marine sediments producing water high in chloride.

As Mr. Ingerson stated, the geology of the San Joaquin Valley is controlling in the occurrence, movement, amount, and chemical character of its ground-water and as our knowledge of its

geology increases with the accumulation of data interpreted by those trained and experienced in engineering geology we will be increasingly able to cope with problems of water-supply, drainage, replenishment, and distribution.

THE HYDROLOGY OF THE SOUTHERN SAN JOAQUIN VALLEY, CALIFORNIA, AND ITS RELATION TO IMPORTED WATER-SUPPLIES

Irvin M. Ingerson

[An abridgment of the paper before the Regional Meeting]

Introduction

This paper presents a technical summary of certain hydrologic and hydrographic factors affecting the continued prosperity of the agricultural activities in the upper or southern portion of the San Joaquin Valley in California, with analyses of service water-requirements and demands upon imported water-supplies from storage on the San Joaquin River.

The data presented herein are from reports of the Division of Water Resources of the State Department of Public Works, Edward Hyatt, State Engineer, and from reports and observations of various public and private agencies and individuals which have collaborated with that Division in the extensive investigations covering the water-resources of the San Joaquin Valley. Particular reference is made to Bulletin No. 29, San Joaquin River Basin, 1931, a publication of the Division of Water Resources. Since the date of that Bulletin continued field-investigations and analyses by the Division have been the direct means of pointing out the engineering and economic feasibility of importing regulated water-supplies.

The writer is indebted to Carl Meyer and other members of the staff of the Division for assistance in collating material for this paper.

Physiography of San Joaquin Valley--The San Joaquin Valley lies in the central portion of the State of California, a relatively level plain of 13,000 square miles, approximately 290 miles long and 50 miles wide between opposing foothills. It rises gradually from sea-level to elevations of approximately 500 feet above sea-level at the bases of the surrounding foothills. The watershed of the San Joaquin Valley amounts to 32,000 square miles of valley and mountain topography ranging from sea-level to a summit of 14,501 feet on Mount Whitney. The San Joaquin River flows northward to join the Sacramento River in a broad inland delta-area and flow together through Carquinez Straits into the San Francisco Bay.

The areal extent of the southern San Joaquin Valley, with which the major portion of this paper is concerned, is the eastern floor of the Valley from the Chowchilla River at the north to Kern Lake at the south, lying east of the trough of the Valley to the foothills of the Sierra Nevada. The elimination of the west-side valley-floor areas is dictated by the facts that the water-supplies from the west-side streams are inadequate to serve any large area and, secondly, that ground-water is limited in amount and uncertain in quality. The portion of the Valley north of the Chowchilla River is also eliminated for the reasons that these lands do and can receive satisfactory water-supplies from their local sources, and ground-water phenomena are not important problems except as difficulties of drainage arise.

Time and space do not permit an exhaustive presentation of the hydrology of the Southern San Joaquin Valley, and we must therefore generalize in order to cover certain of the practical phases of that subject.

Water problems of the Southern San Joaquin Valley

Irrigation-development has been so rapid and extensive in the southern or upper San Joaquin Valley that local water-supplies are now insufficient to meet the needs of present irrigated areas. With limited surface-supplies a full replenishment of ground-water storage is lacking, and in some localities net draft on ground-water storage exceeds the average seasonal replenishment from whatever local sources are available. The result has been a depletion of ground-water storage indicated by continuously receding water-tables. Out of a total irrigated area in the upper San Joaquin Valley of about 1,500,000 acres supplied both from streams and wells, some 400,000 acres are now overdrawing the water-supplies naturally available to them, and studies reveal that only about one-half of the amount necessary for their full requirements is available.

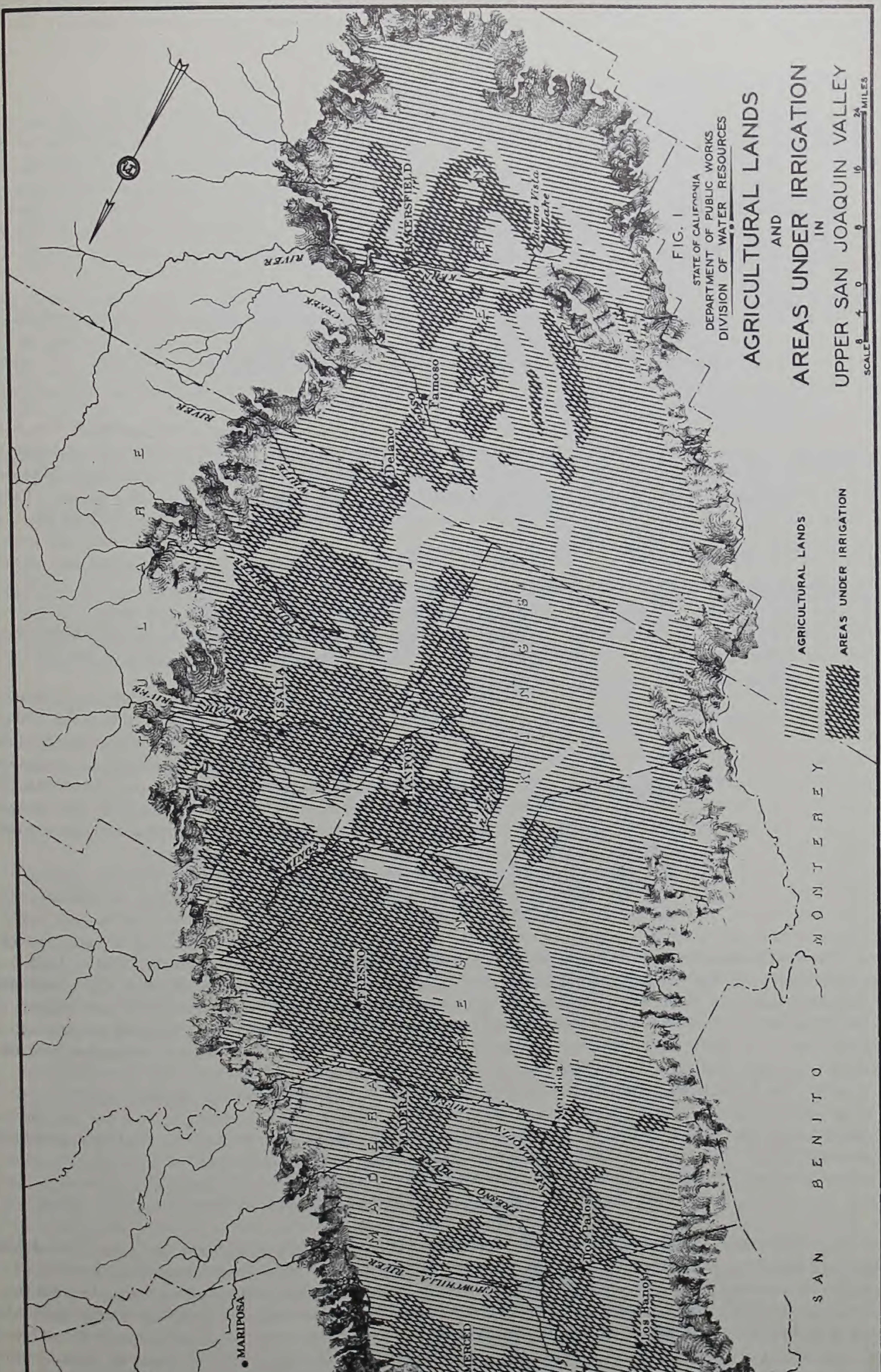


FIG. 1
STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
AGRICULTURAL LANDS
AND
AREAS UNDER IRRIGATION
IN
UPPER SAN JOAQUIN VALLEY
SCALE 8 4 0 8 16 24 MILES
AGRICULTURAL LANDS
AREAS UNDER IRRIGATION
BAKERSFIELD
Buena Vista Lake
Famoso
Delano
VISALIA
HANFORD
FRESNO
MADERA
Mendota
Dos Palos
Los Banos
MERCED
MARIPOSA
MADERA
TULARE
KINGS
KERN
FRESNO
SAN BENITO
MONTEREY

The extent of the agricultural and irrigated lands in the Upper San Joaquin Valley is depicted on Figure 1.

Water-supply for irrigation

Precipitation--The precipitation in the San Joaquin Valley Watershed is extremely variable, both geographically and seasonally. It ranges in seasonal average from 50 inches in the mountains to less than ten inches on the valley-floor, and varies in different seasons and localities from a minimum of 25 per cent to a maximum of over 200 per cent of the mean. Snow prevails in the high mountains and yields a large percentage of the runoff in spring and early summer months. On the average, 90 per cent of the precipitation falls during the months of November to April, inclusive, with little or no rainfall on the valley-floor during the growing season.

Stream runoff--Wide variations in seasonal, monthly, and daily runoff are encountered in all of the streams issuing onto the valley-floor. These variations range from as much as 400 per cent to as little as ten per cent of the 50-year mean. On most of the major streams 75 to 80 per cent of the total seasonal runoff occurs during the five months of the spring and early summer, resulting from melted snows. Daily variations of flow range from practically nothing to several thousand second-feet.

Recharge of ground-water reservoirs--Recharge of the underground reservoirs in the southern San Joaquin Valley is accomplished in part by direct percolation from the major river- and distribution-channels into the relatively porous lenses and stringers of sand and gravels radiating from the apex of each delta, and in part by direct vertical percolation from applied irrigation-water and from wide-spreading flood-flows.

Irrigation-use of water--Irrigation-development has been rapid and extensive, particularly in the last four decades. The area irrigated has increased from about 600,000 acres in 1900 to about one and one-half million acres in 1929. Figures of the Federal census showing the irrigated areas in the Upper San Joaquin Valley south of the Chowchilla River are presented in Table 1. The census figures for 1939 are not yet available.

Table 1--Federal census - irrigated acreage - San Joaquin Valley

Year	County					Census total
	Madera	Fresno	Kings	Tulare	Kern	
1899	23,152	283,737	92,794	86,854	112,533	599,070
1909	38,705	402,318	190,949	265,404	190,034	1,087,410
1919	100,220	547,587	187,868	398,662	223,593	1,457,930
1929	140,637	533,992	269,994	410,683	118,106	1,473,412

In the southern or upper valley, the first irrigation-developments were made by direct surface-diversion to the lands, principally on the delta-fans. For areas distant from streams, where surface-supplies were not obtainable, ground-water was found to be available and pumping began to be practiced in the early part of the present century. Pumping from wells also has been developed to a very large extent in those sections of the Valley where stream-flow is small in relation to the demand. On the deltas of the Kings, Kaweah, and Tule rivers pumping from wells within the irrigated areas is extensively used to supplement direct surface-diversion.

None of the streams tributary to this portion of the Basin are regulated by surface-storage, and the limit of utilization of their surface-runoff under existing diversion-rights has long since been reached. The area of cropped lands irrigated solely from surface-diversions varies with wet and dry periods. On the other hand, the extent of irrigated areas entirely dependent upon a supply pumped from ground-water has been increasing rapidly, even though the water-levels underlying these areas have been receding steadily. In the light, therefore, of the increasing acreage relying upon pumped water for irrigation, it is clearly apparent that the ground-water reservoirs in the southern San Joaquin Valley are assuming primary importance, and effective means of replenishing and husbanding ground-water supplies is essential to the continued well-being of the agricultural enterprises in this area.

Imported water solves ultimate needs--It has been previously pointed out that the water-supply originating in the several streams tributary to the upper San Joaquin Valley, which is being utilized or which could be made available under the fullest practicable development, is insufficient in amount to meet the ultimate water-requirements for all uses in the Basin. The

greatest practicable utilization of the local water-supplies by means of the underground reservoirs in the Upper San Joaquin Valley for storage and subsequent extraction of water results in a minimum of the amount of water to be imported from outside the Basin.

With the consummation of the plans now in progress, regulated water-supplies will be soon available from Friant Reservoir on the San Joaquin River to meet the demand for surface-irrigation requirements and for the replenishment of underground reservoirs through the medium of definite and selected spreading and percolating areas. Waters stored in the Friant Reservoir will be released into two canals, the Madera Canal flowing northward a distance of 40 miles to the Chowchilla River to serve lands of the Madera Irrigation District, and the Friant-Kern Canal flowing southward a distance of 160 miles to Bakersfield on the Kern River. The capacity of the Madera Canal will be 1,000 second-feet and the Friant-Kern Canal 3,500 second-feet. The waters stored in Friant Reservoir on the San Joaquin River are considered to be imported supplies so far as the Upper San Joaquin Valley is concerned for the reason that that stream serves only about 6,000 acres within the area herein considered.

Analyses of ground-water conditions and tributary water-supplies

The purpose of conducting ground-water investigations in the Southern San Joaquin Valley Area, and preparing analyses thereon is to determine the present status of the water-requirements with relation to the contributory supplies, from which can be derived a measure of future economic requirements that must be met by the conservation of local supplies and importation of additional supplies from Friant Reservoir. These studies have been made by the State Division of Water Resources over a period of many years.

<u>Ground-water investigations</u>--A comprehensive investigation of the ground-water conditions under the lands on the east side of the southern San Joaquin Valley from the Chowchilla River south to Kern Lake has been continued by the State Engineer's office since about 1920. Numerous furtherances of the investigations have at times been made in cooperation with various local agencies through their representatives and consulting engineers.

<u>Ground-water measurements</u>--In a valley-wide comprehensive study of ground-water conditions, it has been the practice of the Division to obtain each year depth to ground-water measurements on some 2,000 wells between Chowchilla River and Kern Lake on the east side of the valley-trough. These measurements are made during the fall season of the year. A measuring-point elevation on each well has been established by closed level-circuits and the depth from the measuring point to the water-surface in the well is obtained by a steel tape. The elevation of the water-table on United States Geological Survey Datum at the time of measuring is thereby obtained.

<u>Surface water-supply investigations</u>--Water-supply studies on the various streams and irrigated areas have been in more or less continuous progress by the Division not only on account of the furtherance of the State Water Plan, but also as part of code prescribed activities of the State Engineer's Office. Major reliance is made upon the records of stream-flow available from the United States Geological Survey. However, where concerted studies have been made on certain areas the Division has established and maintained additional gaging stations in order to augment the Survey's records. In the Southern San Joaquin Valley Area there is by no means a sufficient number of hydrographic stations to yield a completely satisfactory rounding-out of information to fill the gaps.

<u>Ground-water maps</u>--Three types of ground-water maps are being prepared by the Division covering the upper or southern San Joaquin Valley, namely, ground-water elevation contour-maps for the fall season of each year, a map for each year showing lines of equal depth to ground-water, and at three- or four-year intervals a map showing lines of equal total change between ground-water-table elevations of any two certain years. The usual and well-recognized methods of preparing the ground-water maps are employed by the Division.

Some features regarding ground-water conditions of the Valley can be shown for the area as a whole, and the ground-water maps serve this purpose. Figure 2 shows "Lines of equal elevation of ground-water table in Upper San Joaquin Valley, fall of 1939." This map indicates the direction of movement and the probable sources of the ground-water. The general slope is from the east side of the Valley toward the Valley trough. Ground-water cones are built up under the deltas formed by some of the streams. The effect of excessive ground-water draft in some localities is shown in the resulting ground-water depressions. Of particular interest are the depressions in the vicinity of Richgrove and of Lindsay. The effect of streams in building up the adjacent ground-water is illustrated by the ground-water contours near Kern River and in the upper portions of the Tule and Kaweah deltas. The San Joaquin River where it enters the Valley


MARIPOSA
CO.
MADERA
CO.
MADERA
FRESNO
MERCED
FRESNO
CO.
CO.
Ben Hur
Raymond
Knowles
O'Neals
Daulton
Friant
Friant Res.
MINARETS
AND
WESTERN
EASTERN
Grabners
Academy
SAN
JOAQUIN
RIVER
Prado
Clovis
Chowchilla
Dutchman
Deadman
Creek
River
Cr.
Sharon
ATCHISON
TOPEKA
AND
SANTA FE
SOUTHERN
PACIFIC
Trigo
Gregg
Herndon
Berenda
Fairmead
Gravelly
Aliso
Cottonwood
Ford
Canal
Chowchilla
Dairyland
Ash
Fresno
Bola
Kerman
Kearney Park
Dry
Creek
Lonewillow
Slough
Poso
Columbia
Dos
Palos
Firebaugh
Outside
Main
No. 1
No. 2
No. 3
Mendota
MENDOTA IRR. DIST.
FRESNO IRRIGATION
Tranquillity
James
San Joaquin
By-Pass
Slough
Oro Loma
Little Panoche Cr.
Panoche
Arroyo
Cantua
Cr.
7
8
9
10
11
12
13
14
15
16
17
18
19
11
12
13
150
160
200
225
250
275
300
175
FIG. 2(A)

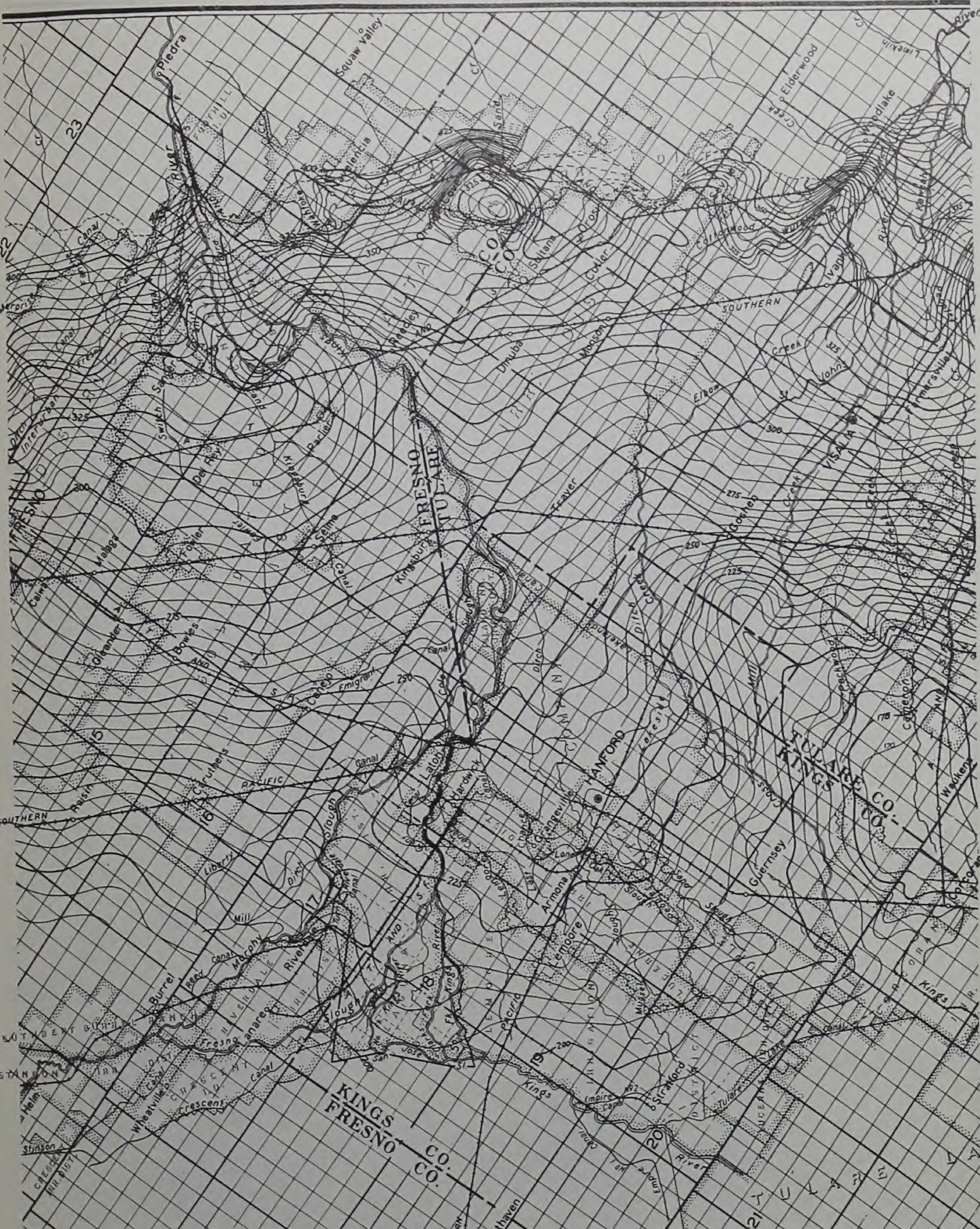

Piedra
Squaw Valley
Elderwood
Woodlake
River
SOUTHERN
Dinuba
Sultana
Cutler
Reedley
Traver
Visalia
Goshen
Kingsburg
Selma
FRESNO
TULARE
Del Rey
Fowler
Malaga
Bowles
Caruthers
Raisin
PACIFIC
Liberty
Burrel
Laton
Hardwick
HANFORD
Grangeville
Armona
Lemoore
Guernsey
TULARE CO.
KINGS CO.
Stratford
KINGS CO.
FRESNO CO.
Westhaven
Huron
Murray
Riverdale
Crescent
Wheatville
Stinson
Helm
Corcoran
Waukena
Farmersville

FIG. 2(B)


Lemon Cove
Springville
TULE RIVER
Fork
INDIAN
RESERVATION
South
California
Hot Springs
Creek
Yokohl
Porterville
Slough
River
White
White River
Deer
Creek
Poso
Porter
Pixley
Earlimart
Allensworth
Delano
McFarland
Famosa
Pond
Wasco
Shafter
Angiola
Alpaugh
ATCHISON
TOPEKA
AND
Lake
Shore
R.R.
Little
Woody
Lost Hills
Buttonwillow
KINGS
CO.
TULARE
KERN
S.P.R.R.
20
21
22
24
25
26
27
28
29
30
FIG. 2(C)

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
CENTRAL VALLEY PROJECT

LINES OF EQUAL ELEVATION OF GROUND WATER TABLE IN UPPER SAN JOAQUIN VALLEY FALL OF 1939

SCALE OF MILES

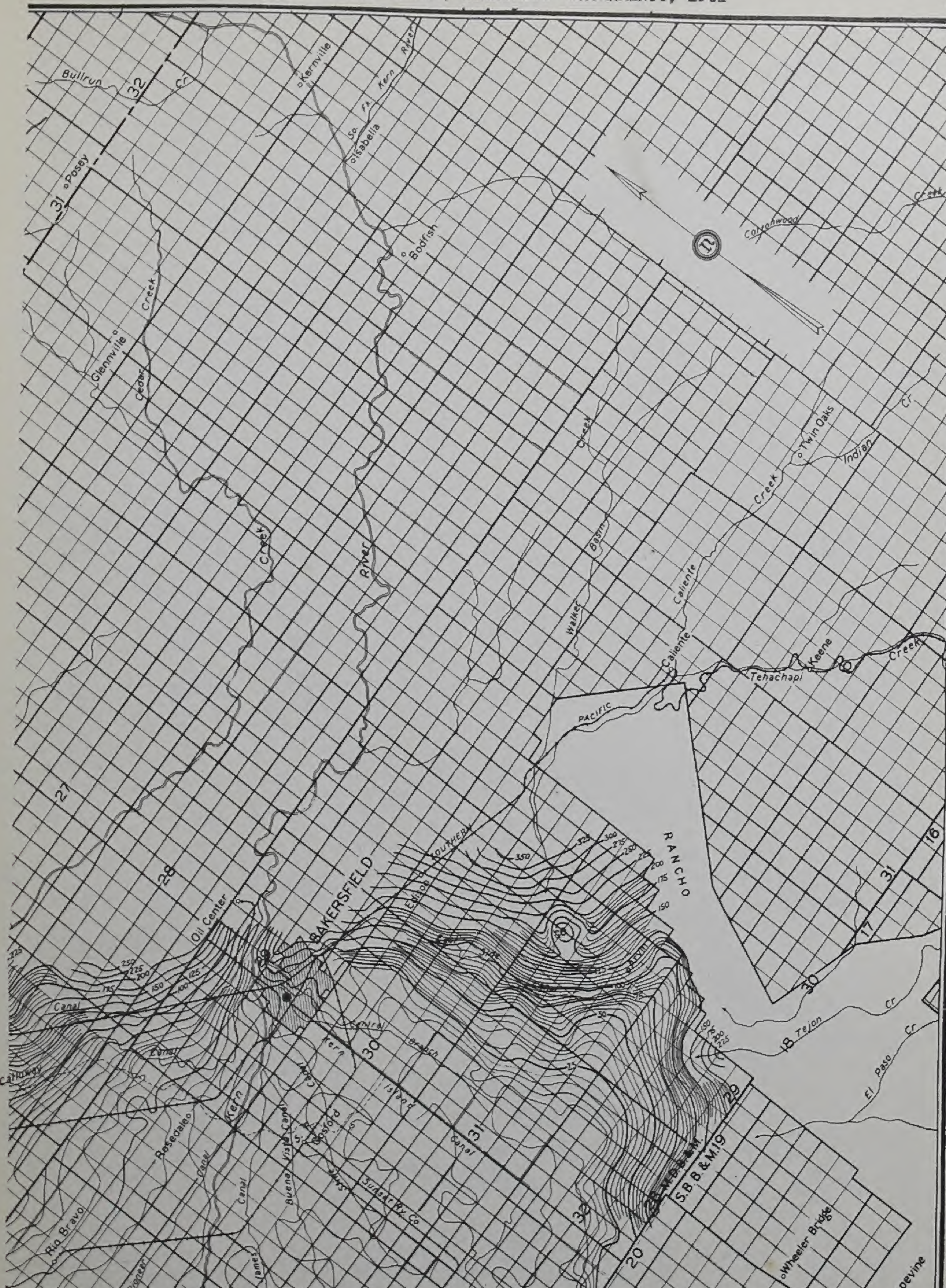
FIG. 2(D)


Ben Hur
MARIPOSA
CO.
Raymond
Knowles
O'Neals
Friant
Friant Res.
Grabners
Academy
MINARETS
AND
WESTERN
EASTERN
SAN
JOAQUIN
Creek
Chowchilla
MADERA
CO.
Berenda
Fairmead
Sharon
Dry Cr.
River
ATCHISON
SANTA FE
SOUTHERN
PACIFIC
MADERA
Trigo
Gregg
Herndon
Biola
Clovis
Gould
FRESNO
Kearney Park
Kerman
Gravelly
Aliso
Cottonwood
Ford
Canal
Chowchilla
Canal
Lonewillow
Slough
Poso
Columbia
Canal
Dos Palos
Outside
Firebaugh
Main
Mendota
Tranquillity
James
By-Pass
San Joaquin
Slough
MENDOTA IRR. DIST.
Oro Loma
MERCED
FRESNO
CO.
CO.
Little Panoche Cr.
Panoche Cr.
Cantua
Arroyo
Hondo
7
8
9
10
11
12
13
14
15
16
17
18
19
21
22

FIG. 3(A)


Piedra
Squaw Valley
Elderwood
Woodlake
Orosi
Sultana
Cutler
Monson
Dinuba
Reedley
Traver
Goshen
VISALIA
Farmersville
Kaweah
Elbow
St. Johns
Parlier
Del Rey
Sanger
Selma
Fowler
Malaga
Kingsburg
Oleander
Bowles
Caruthers
Raisin
Laton
Hardwick
HANFORD
Grangeville
Lemoore
Armona
Guernsey
Stratford
Riverdale
Burrel
Helm
Stinson
Wheatville
Westhaven
Huron
Murray
Lakeside
Cameron
Waukena
FRESNO
TULARE
TULARE CO.
KINGS CO.
KINGS CO.
FRESNO CO.
Liberty
Mill
Ditch
Canal
Slough
Kings River
Empire
Tulare
Crescent
Fresno
Emigrant
Lone Oak
FIG. 3(B)


TULE RIVER
INDIAN
RESERVATION
South
Fork
Springville
California
Hot Springs
Yokohl
Creek
Porterville
Slough
River
Creek
White River
White
River
Woody
Porter
Tipton
SOUTHERN
PACIFIC
Pixley
Earlimart
Deer
Creek
Richgrove
Ducor
Delano
McFarland
Pond
Wasco
Shafter
Allensworth
Angiola
ATCHISON
TOPEKA
Alpaugh
BASIN
Shore
Elk
Bayou
KINGS
CO.
TULARE
CO.
KERN
CO.
Lost Hills
Buttonwillow
Little
Creek
20
21
22
24
24
25
25
26
27
28
29
30
FIG. 3(2)



STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
CENTRAL VALLEY PROJECT

LINES OF EQUAL DEPTH
OF
GROUND WATER TABLE
IN UPPER SAN JOAQUIN VALLEY
FALL OF 1939

SCALE OF MILES

FIG. 3(D)

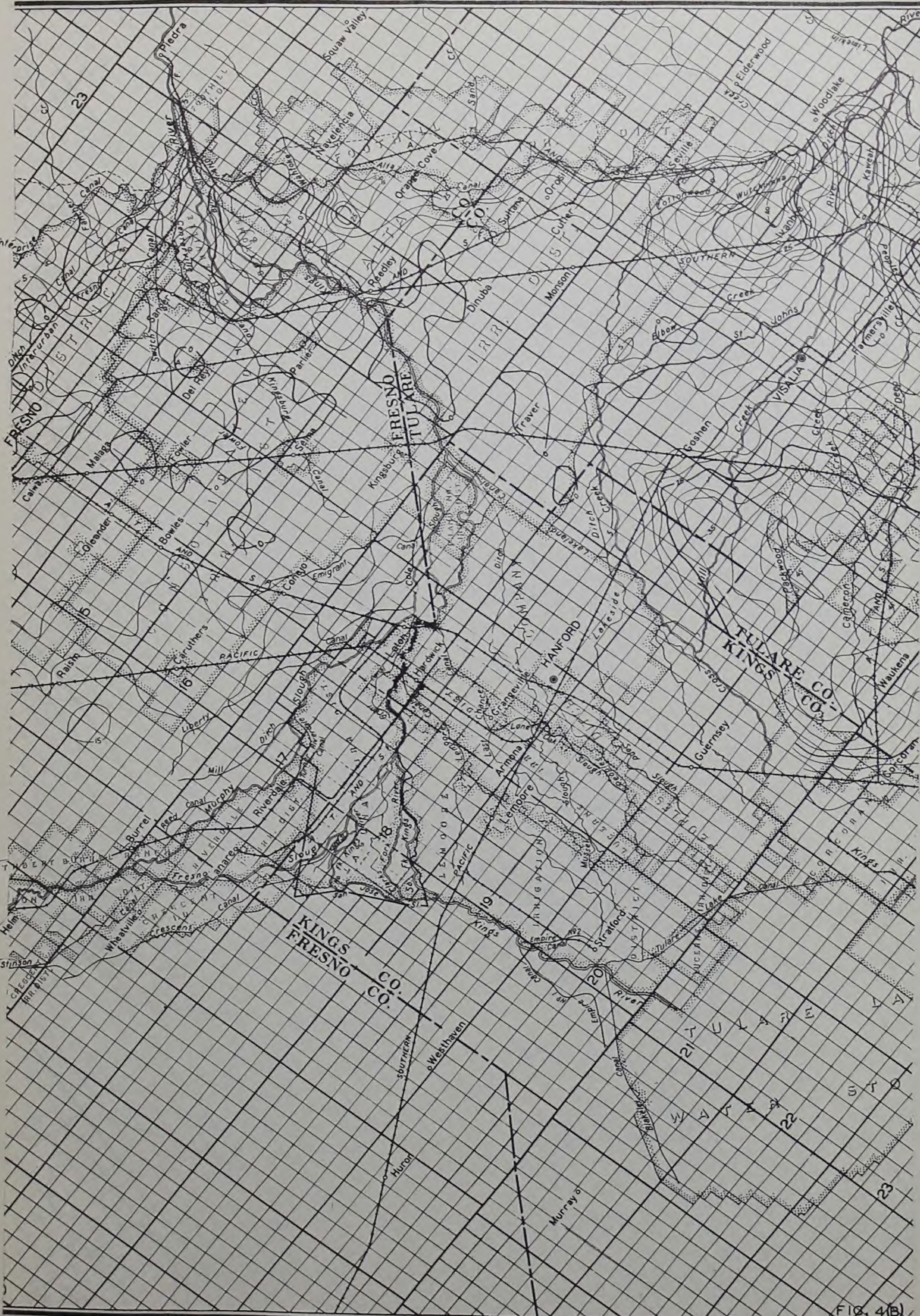

Piedra
Squaw Valley
Navelencia
Orange Cove
Reedley
Dinuba
Orosi
Cutler
Monson
Seville
Elderwood
Woodlake
Traver
Kingsburg
Selma
Fowler
Malaga
Sanger
Del Rey
Parlier
Oleander
Bowles
Caruthers
Raisin
Congo
Laton
Hardwick
HANFORD
Grangeville
Armona
Lemoore
Riverdale
Burrel
Helm
Stinson
Westhaven
Huron
Murray
Stratford
Guernsey
Corcoran
Waukena
Goshen
VISALIA
Farmersville
FRESNO
TULARE
KINGS
TULARE CO.
KINGS CO.
KINGS CO.
FRESNO CO.
SOUTHERN
PACIFIC
Elbow
Creek
St. Johns
Kaweah
River
Lakeside
Cross
Sand
Slough
Empire
Tulare
Lake
Canal
Emigrant
Liberty
Mill
Ditch
Murphy
Reed
Fresno
Crescent
Westside
San Jose
Enterprise
Interurban
Wutchumna
Cottonwood
Cameron
Packwood
Lone
Last Chance
Blakeley
Chance
Ditch
15
16
17
18
19
20
21
22
23
23

FIG. 4(B)

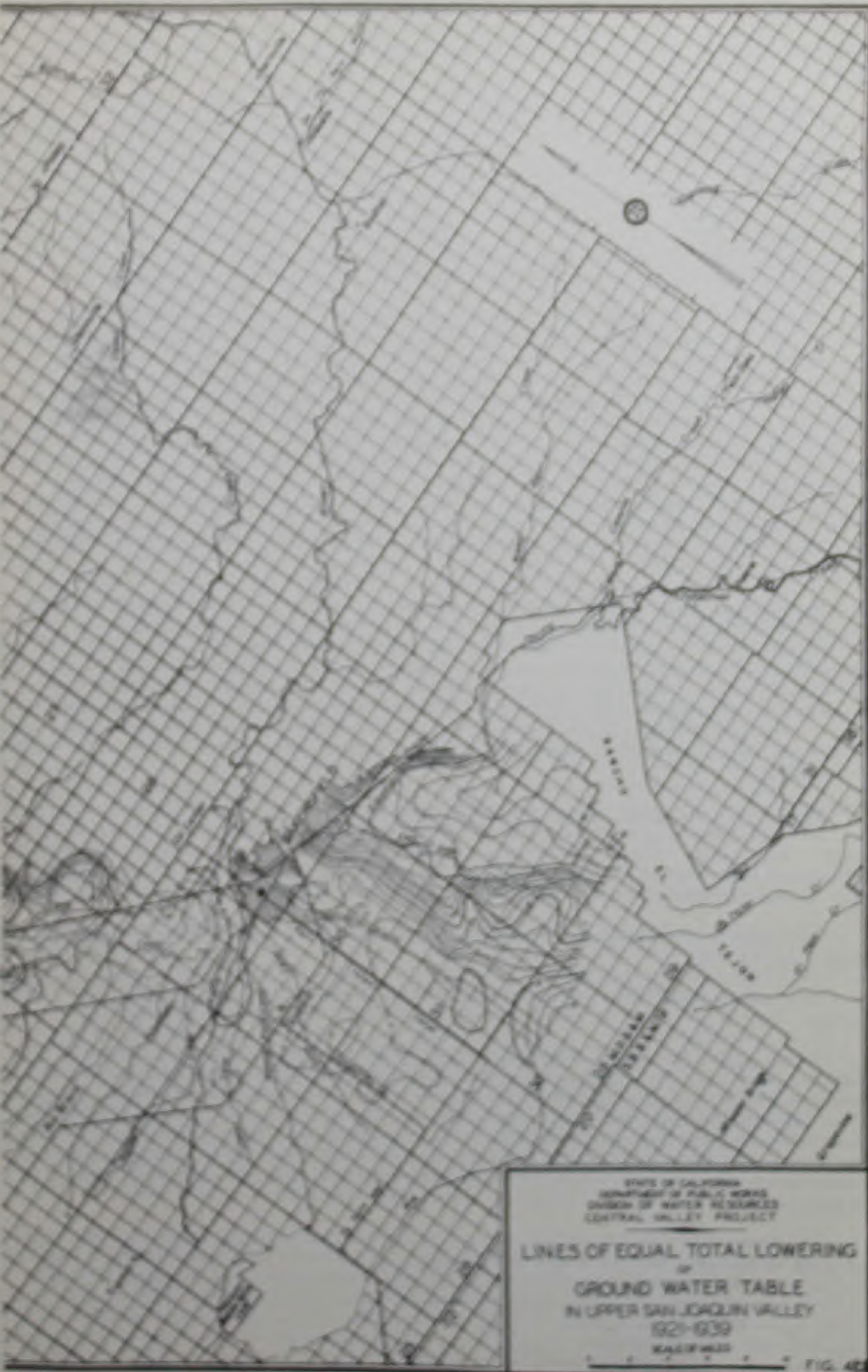
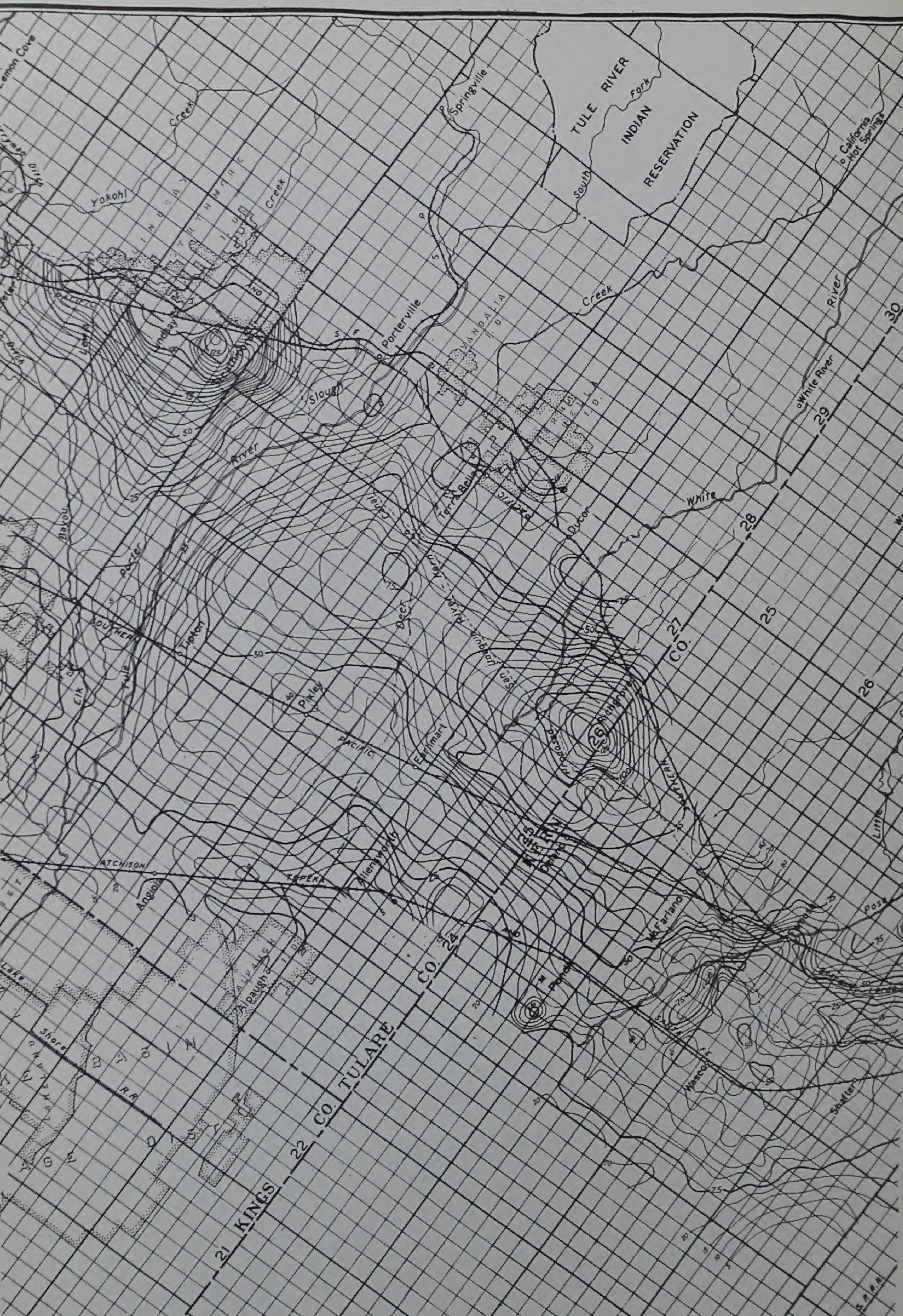

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
CENTRAL VALLEY PROJECT
LINES OF EQUAL TOTAL LOWERING
OF
GROUND WATER TABLE
IN UPPER SAN JOAQUIN VALLEY
1921-1939
SCALE OF MILES

FIG. 4


Lemon Cove
TULE RIVER
INDIAN
RESERVATION
Springville
California Hot Springs
Yokohl
Creek
Porterville
Lindsay
Strathmore
Slough
River
Poso
White River
White
Ducor
Terra Bella
Deer
Creek
Tipton
Pixley
Earlimart
Delano
Richgrove
Allensworth
Angiola
Alpaugh
McFarland
Wasco
Shafter
Lost Hills
Buttonwillow
KINGS CO.
TULARE CO.
KERN CO.
Lake
Shore
20
21
22
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29
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FIG. 4(c)

floor is in a deep channel as much as 90 feet below the level of the Valley floor and consequently can not contribute to ground-water to the extent possible from streams on alluvial deltas.

Figure 3, "Lines of equal depth to ground-water table in Upper San Joaquin Valley, fall of 1939," shows the difference in elevation between the ground-water contours delineated on Figure 2 and the ground-surface. The depth to ground-water, as shown on this Figure plus the drawdown while pumping, would represent the total pumping lift to ground-surface at any particular location. For usual rates of pumping, drawdowns in the more open materials vary from 10 to 25 feet and in the finer materials from 25 to 50 feet. While depths increase from the Valley trough toward the east, local increases in depths result from heavy pumping draft in areas away from direct sources of water-supply. The effect of canal service in maintaining a relatively higher ground-water table is shown under the canals extending from the Kern and Kings rivers.

Figure 4, "Lines of equal total lowering of ground-water table in Upper San Joaquin Valley, 1921 to 1939," shows differences in ground-water-table elevations that have occurred in the 18-year period for those parts of the area for which records are available. For most areas shown there has been a lowering between those dates, but the maximum lowering occurred in the fall of 1934 following a series of subnormal years of rainfall and runoff and consequently increased pumping draft. This Figure brings out more forcibly than Figures 2 and 3 the large variation in lowering in different areas. The amount of lowering is generally proportional to the distance from direct sources of ground-water supply and the amount of pumping draft. In areas of heavy pumping which have direct sources of water-supply, such as the areas adjacent to the river-channels or distributaries, the lowering has been a minimum of five to ten feet. Outside of canal-served areas, lowerings of more than 130 feet have occurred. Small areas of rise of water-table occurred on the apex of the deltas of the Tule, Kaweah, and Kings rivers and near Pinedale in Fresno County.

<u>Ground-water units</u>--Ground-water conditions vary so widely in the different local areas that generalizations or averages are of limited assistance in studying the problems of the Upper San Joaquin Valley. A study of ground-water conditions in each local area is necessary for a determination of present needs and for the formulation of any plans for the relief of present overdrafts, as ground-water storage is an essential part of the plans for such relief. The boundaries of the smaller areas, designated as units, were determined by local conditions of influence upon ground-water. Such conditions of influence include characteristics of ground-water elevations, of surface-water supply and its extent, of diversion and utilization, of soils, and of topography.

<u>Methods of analysis to determine ultimate requirements</u>--Several irrigated areas in the Upper San Joaquin Valley are now developed on the basis of reuse of the percolation to the ground-water. Consequently in plans for meeting the water-requirements of such areas it is necessary to estimate the amount of "net use." At this time in this paper it is best to incorporate certain definitions in order to clarify the terms and methods discussed.

"Consumptive use" designates the amount of water actually consumed through evaporation and plant-transpiration.

"Net use" designates the sum of consumptive use from artificial supplies and irrecoverable losses.

For any particular ground-water unit or basin, the portion of the net use termed "irrecoverable losses" comprises ground-water outflow from the unit, if any occurs, water consumed by natural vegetation in uncultivated or non-cropped areas, and all other water lost or consumed other than that consumed directly in connection with the application of water for crop-irrigation. An absorptive area receiving an average water-supply equal to its net use would maintain its ground-water elevations without progressive rise or fall. Amounts of gross pumping draft in excess of the net use percolate back to the ground-water and become available for reuse by subsequent pumping. Net use, as defined, does not include rainfall.

"Drainage-factor" designates the per cent of the total soil-volume occupied by the water obtained by drainage, and which will be numerically the same as that required for its resaturation. An assumed drainage-factor is not used in this method of analysis since it is assumed that the average annual depletion in volume of ground-water in any unit is equal to the average annual shortage in volume of water for net-use requirements. The actual value of the drainage-factor is indicated by the ratio of the average annual depletion, in acre-feet, to the average annual volume of soil drained, expressed also in acre-feet. It is therefore, necessary to bring into any ground-water unit or basin sufficient water only to meet the net use.

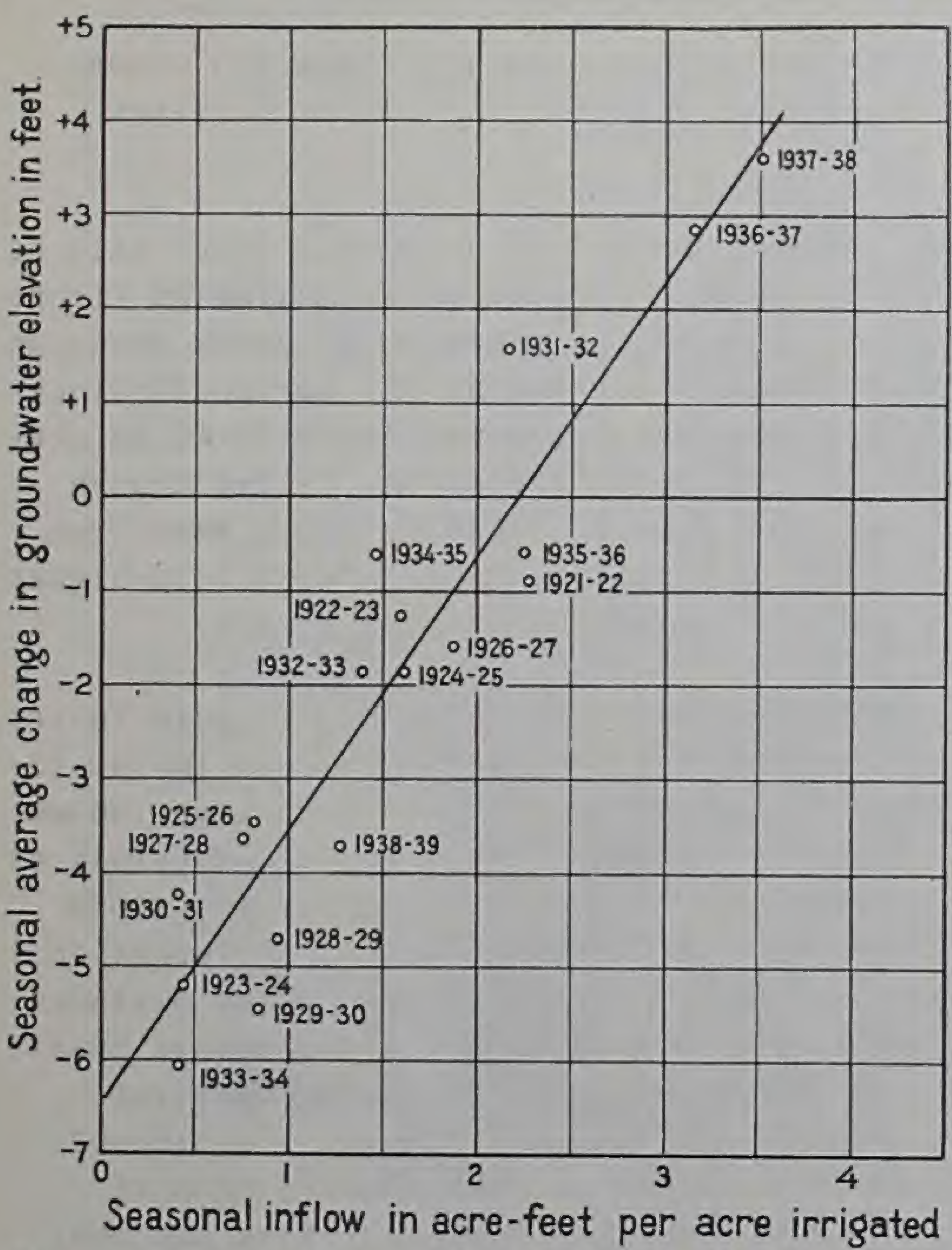


Fig. 5--Tule River-Deer Creek Area, relation of seasonal inflow to change in ground-water elevation, 1921-1929

The method used is a modification of that first used by Professor S. T. Harding of the University of California in San Joaquin Valley ground-water studies. It consists in plotting the water-supply for each season in terms of acre-feet of measurable inflow per acre irrigated against the change in ground-water elevation, in feet, for the season. Such plotting for different years indicates the relationship between supply and changes in ground-water level. A mean line expressing such relationship is drawn. The intersection of this line with the zero-line of the scale of fluctuation indicates, on the scale for inflow, the acre-feet per irrigated acre needed to meet the net use, including the difference between unmeasurable inflow and outflow, without progressive ground-water change. The supply used is the sum of all measurable sources of inflow, less all measurable items of outflow. The product of the unit net use so determined and the average area irrigated during the period of record shows the mean seasonal net supply which would have been necessary to meet the crop-requirements and irrecoverable losses without rise or fall of the water-table. The difference between the seasonal inflow, thus derived, and the mean actual inflow for the period indicates the average shortage of supply for areas where lowering has occurred. This method of analysis assumes that the requirements for net use are met in all years without shortage. This condition is generally met for lands served from wells, but is not always met in years of deficient canal supplies for crops wholly dependent upon canal service. The method includes, in the determination of net use, the immeasurable net difference between the ground-water inflow and outflow and water used by natural vegetation and uncultivated areas. These inclusions result in variations in net use per unit of area of irrigated crops in different ground-water units. This method is mathematically correct only when the annual irrigated area in each unit remains constant, but the variations in other physical factors probably introduce wider deviations in net-use results than does the variation in irrigated area. The method also is based upon the assumption that the drainage-factor is constant throughout the full stratum of fluctuation.

For a concrete illustration of the application of this method, the results of a recent analysis made by the Division for the Tule-Deer Creek ground-water unit are presented.

The gross area of the Tule-Deer Creek unit is 373 square miles or 238,720 acres. The average area irrigated for the 18-year period, 1921-1939, was 67,800 acres, and the average seasonal net surface-water contribution was 103,540 acre-feet, or 1.53 acre-feet per acre irrigated. The average seasonal lowering of the ground-water table was 2.06 feet. The relation between net surface-water contributions per acre irrigated and changes in ground-water elevation is presented graphically for each season of the 18-year period on Figure 5. It is demonstrated on the Figure that a seasonal net surface-water contribution to the area of 2.22 acre-feet per acre irrigated would meet crop needs and maintain a constant ground-water level. The average seasonal water-requirements for this area equals the product of 67,800 acres and 2.22 acre-feet per acre or 150,500 acre-feet. The average seasonal depletion equals the difference between 150,500 acre-feet and 103,540 acre-feet, or 46,960 acre-feet. The average seasonal soil-volume drained equals the product of 238,720 acres and 2.06 feet, or 491,800 acre-feet. Therefore, the drainage-factor equals 46,960 acre-feet divided by 491,800 acre-feet, or 9.5 per cent. The data supporting these foregoing results are shown in Table 2.

In a parallel study of suitability of lands for agricultural use, the Division has determined that the ultimate net irrigable areas in this Tule-Deer Creek unit will probably amount to only two-thirds of the gross area. Based upon exhaustive studies of other areas in the Upper San Joaquin Valley, it is concluded that the present net use of 2.22 acre-feet per acre irrigated will be decreased slightly when a larger proportion of the unit's area comes under irrigation, and that therefore ultimate net-use requirements will amount to 2.0 acre-feet per acre irrigated. On this basis the estimated ultimate average annual net-use requirements would be the

Table 2--Seasonal water-supply, area irrigated, and groundwater-changes in Tule River-Deer Creek groundwater unit

Area of groundwater unit, 373 square miles

Season, October 1 to September 30	Area irrigated, acres	Surface-water contributions to ground-water unit, in acre-feet					Average seasonal change of groundwater-elevation, feet	Average depth to groundwater at end of season, feet
		Runoff of Tule River	Runoff of Deer Creek	Estimated surface-outflow	Net surface-water contributions			
					Total	Per acre irrigated		
								39.46
1921-22	64,500	139,700	16,500	9,700	146,500	2.27	-0.89	40.35
1922-23	65,300	102,000	14,200	12,100	104,100	1.59	-1.27	41.62
1923-24	66,100	24,700	4,600	0	29,300	0.44	-5.20	46.82
1924-25	67,000	89,800	17,200	0	107,000	1.60	-1.87	48.69
1925-26	67,800	48,900	7,100	0	56,000	0.83	-3.47	52.16
1926-27	68,600	131,000	15,100	17,600	128,500	1.87	-1.60	53.76
1927-28	69,400	48,200	8,400	4,600	52,000	0.75	-3.64	57.40
1928-29	70,200	54,800	11,300	0	66,100	0.94	-4.70	62.10
1929-30	67,000	46,400	8,300	0	54,700	0.82	-5.46	67.56
1930-31	61,600	20,400	5,000	0	25,400	0.41	-4.22	71.78
1931-32	66,800	133,900	18,700	8,100	144,500	2.16	+1.59	70.19
1932-33	67,000	80,800	12,800	0	93,600	1.40	-1.87	72.06
1933-34	62,000	22,200	3,800	0	26,000	0.42	-6.05	78.11
1934-35	68,900	90,700	13,100	3,900	99,900	1.45	-0.61	78.72
1935-36	68,900	162,600	21,900	30,300	154,200	2.24	-0.58	79.30
1936-37	71,000	284,100	50,900	112,200	222,800	3.14	+2.83	76.47
1937-38	73,000	332,000	53,600	127,500	258,100	3.54	+3.60	72.87
1938-39	75,000	82,800	13,800	1,500	95,100	1.27	-3.71	76.58
Averages	67,800	105,280	16,460	18,200	103,540	1.53	-2.06	-----

Average seasonal water-requirements, 67,800 x 2.22 .... 150,500 acre-feet
Average seasonal net surface-water contribution .... 103,540 acre-feet
Average seasonal depletion .... 46,960 acre-feet
Average seasonal soil-volume drained 2.06 x 373 x 640 .... 491,800 acre-feet
Average drainage-factor .... 9.5 per cent

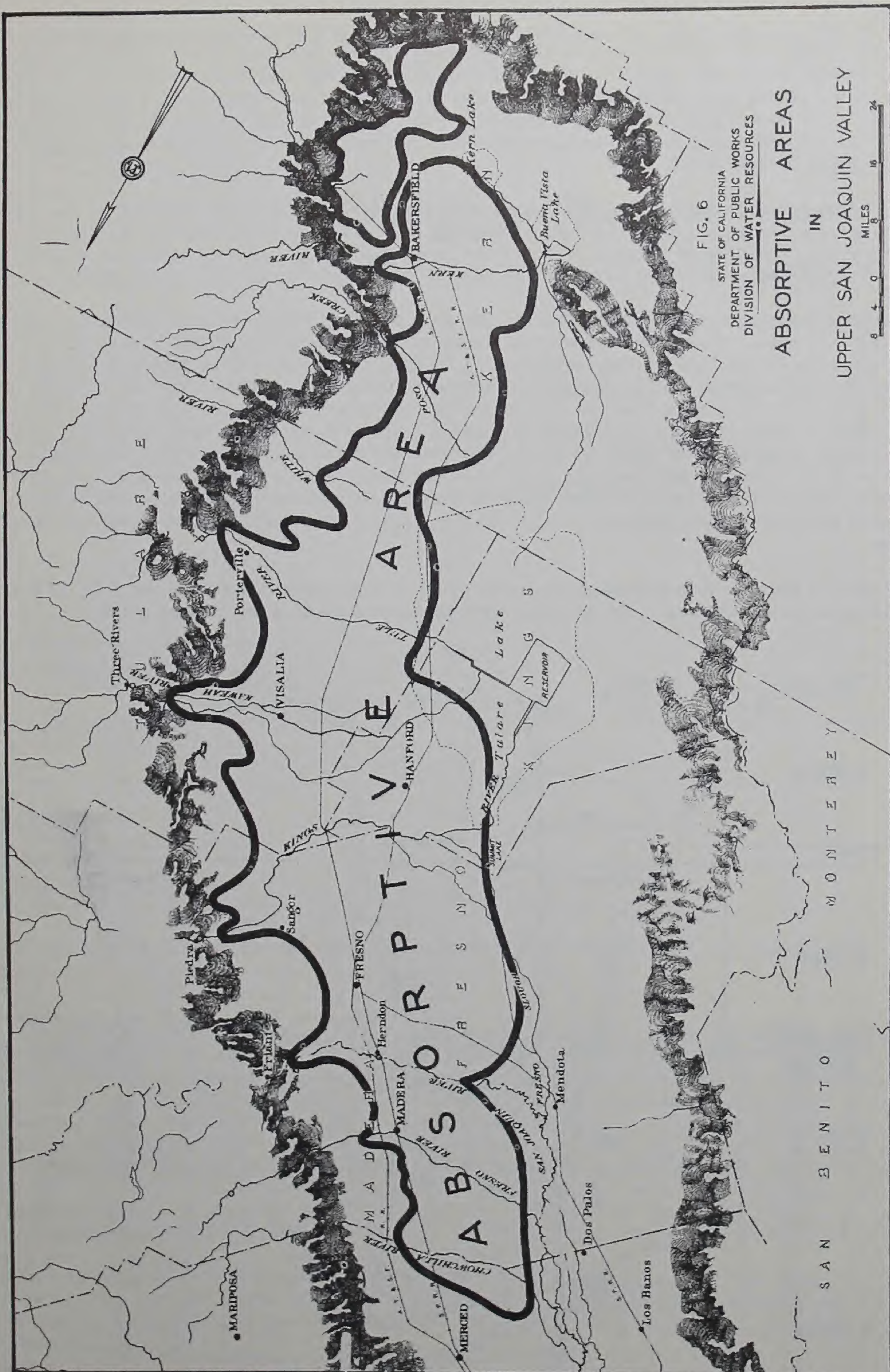
product of 238,720 acres, 2.0 acre-feet per acre, and 0.67, or 323,000 acre-feet in round figures. Therefore, the average annual supplemental water-requirements for this area in question is the difference between 323,000 acre-feet and 103,500 acre-feet or 219,500 acre-feet. This last figure is the answer desired in this foregoing analysis, namely, a measure of the ultimate demand by this particular area upon the foreign waters to be imported.

Factors affecting southern San Joaquin Valley ground-water phenomena

In the following it is desired to point out some of the important factors which are having or may have in the future, considerable effect upon a continuous and successful employment of the ground-water reservoirs as a secondary or cyclic source of water-supply for irrigation.

The area of the Upper San Joaquin Valley, lying south of the topographic ridge extending across the Valley floor due to the delta of the Kings River, overlays a vast ground-water basin from which there is no escape of water except by evaporation or plant-transpiration. The ground-water under this basin is replenished mainly by percolation of contributory stream-flow. Probably the most important factor which must be taken fully into account in planning the details of water-distribution of imported water-supplies is the widely varying types of soils and sub-soils. The granular structure of the sub-soils between the surface and the lowest zone of possible ground-water extraction is by no means homogeneous. Any designed plans depending upon extensive lateral movement of seasonally applied water for ground-water replenishment may not be fulfilled owing to the frequent occurrence of relatively impervious horizons and bodies which substantially retard free movement.

The predominant features of the material filling the great inland trough between the Sierra



Nevada on the east and the Coast Range on the west is the fact that it was laid down in the more or less quiescent waters of a large inland lake or arm of the sea. This fact accounts for the generally fine-textured materials composing the major portion of the aquifers and for the gradation of the sub-aqueous deposits in extensive horizontal layers.

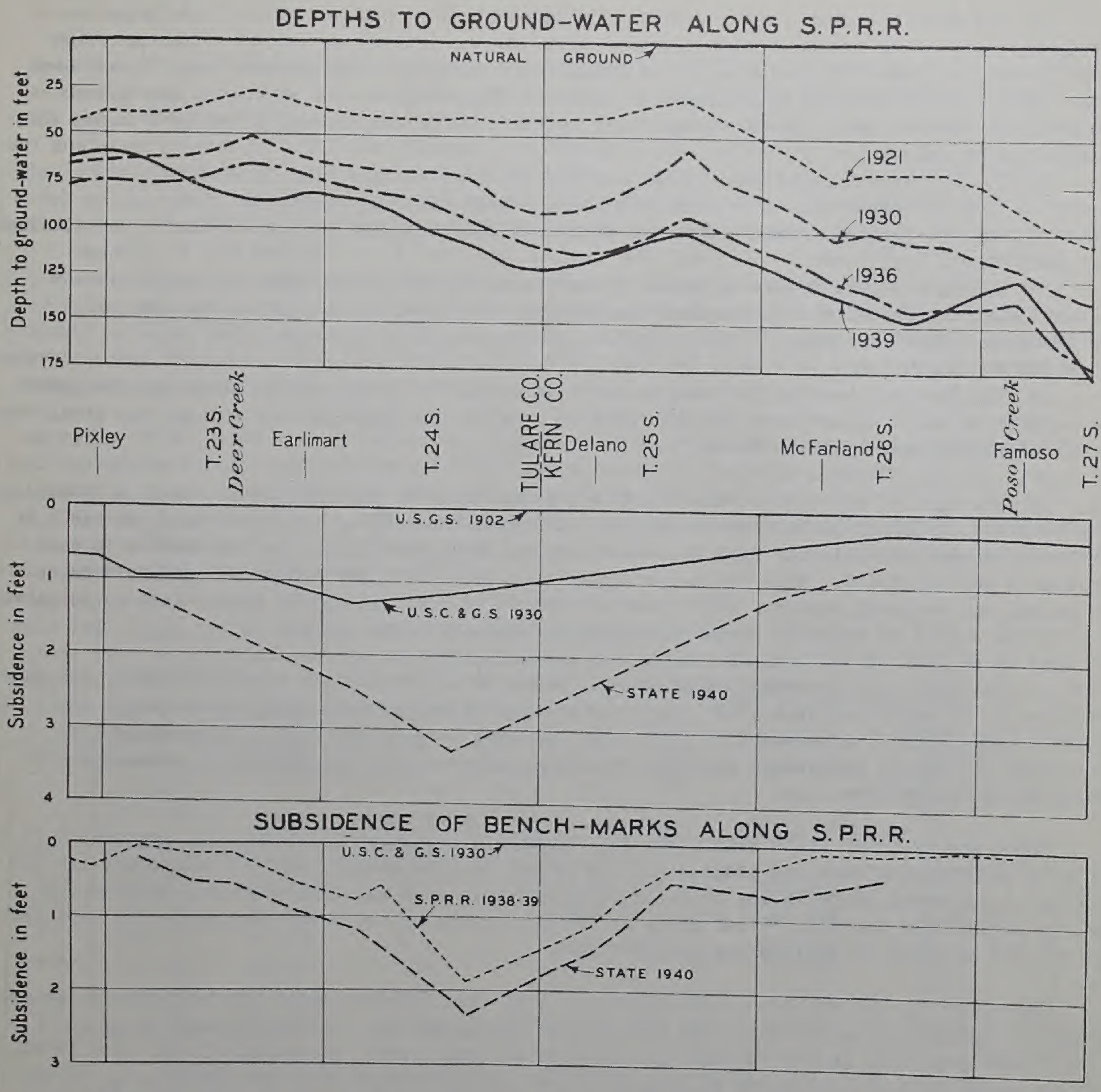


Fig. 8--Depths to ground-water and subsidence-profiles, 1902-40, in Delano Area

Figure 8 shows a profile along the Southern Pacific Railroad running north and south through the subsidence-area, and about one and one-half miles west of the major axis of the cone of depression. The points used in plotting these profiles are actual elevations on United States Geological Survey and United States Coast and Geodetic Survey bench-marks on the right-of-way, determined in 1902, 1930, 1938, and 1940. The levels of 1902 were United States Geological Survey; in 1930, United States Coast and Geodetic Survey; in 1938, Southern Pacific Railroad; and State in 1940. Figure 8 also shows profiles of depths to ground-water for the years 1921, 1930, 1936, and 1939. It is pointed out on this Figure that the bench-mark subsidence shown in the lower diagram is to be added to the subsidence of 1902-1930 of the middle diagram to give a total subsidence from 1902 to 1940.

With these observational data available, the first question arising is the cause for this land-subsidence, and the second question is the extent of the effect the subsidence may have upon conveyance-works crossing the area as part of any major distribution canal for imported water-supplies.

The cause of this subsidence can not be definitely stated at this time, and only apparent coincidental phenomena can be pointed out. These phenomena may be effective to a greater or lesser degree as follows:

The location and extent of the absorptive areas in the San Joaquin Valley is depicted on Figure 6. This area represents in general the extent of the more recent or modern alluvium soils, through which some percolation of greater or lesser rate may be expected. It has been demonstrated in the text and appendices of Bulletin No. 29 of the Division of Water Resources that the gross absorptive areas in the Upper San Joaquin Valley aggregate 2,420,000 acres and have total estimated utilizable storage-capacities of some 20,000,000 acre-feet lying along the eastern slope of the Valley floor.

Surface subsidence in Delano Area--Some time during 1935 Consulting Engineer I. H. Althouse of Porterville called attention to the possibility of a definite subsidence of the ground-surface in the vicinity of Delano. Certain levels he had run in the area showed a definite trend away from the elevations given on the maps of the United States Geological Survey.

During the summer and fall of 1940 the Division of Water Resources conducted field-surveys covering this area. Level-circuits were extended westward across the Valley floor from bench-marks situated at the base of the foothills. A total of about 100 United States Geological Survey and United States Coast and Geodetic Survey bench-marks were checked into the circuits together with over 500 observations of section-corner elevations. The result of these field-levels was to show an area having a subsidence in excess of one foot extending from Famoso northward to about Pixley, a distance of about 25 miles, and from Richgrove westward to Pond, a distance of about 14 miles. The maximum measured subsidence was 5.00 feet, occurring one-half mile east of the main line of the Southern Pacific Railroad and three miles north of Delano. These subsidences are based upon elevations published by the United States Geological Survey as shown on topographic maps.

Figure 7 depicts this subsidence area by lines of equal subsidence from one foot to 5.00 feet at half-foot intervals. The affected area embraces more than 200 square miles.

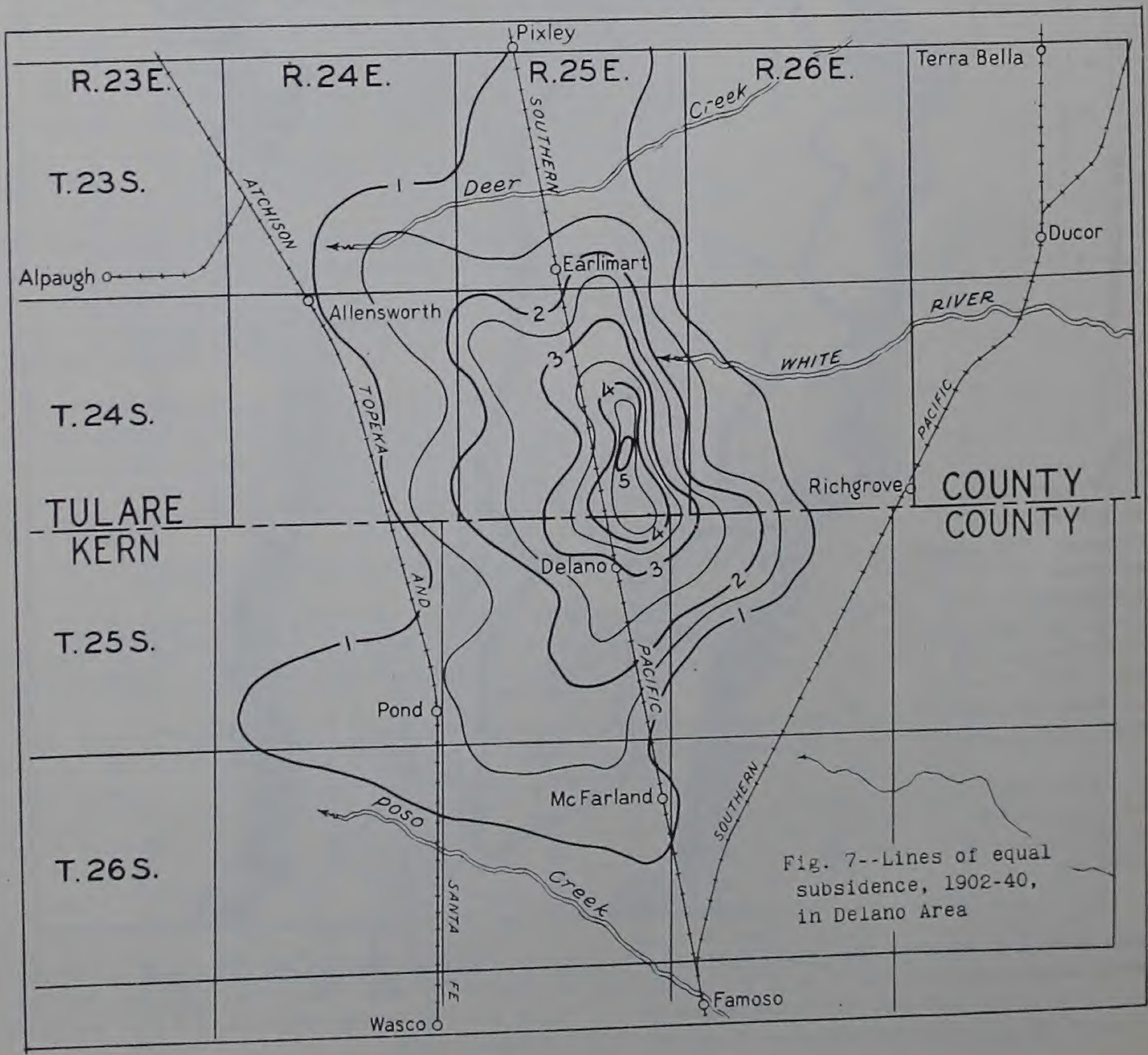


Fig. 7--Lines of equal subsidence, 1902-40, in Delano Area

(1) The greatest total lowering of the ground-water from 1921 to 1939 in the Upper San Joaquin Valley occurs within this subsidence-area but not entirely concentric thereto. Reference is made to Figure 4 showing lines of equal total lowering. The average total lowering in this period has amounted to approximately 100 feet. This indicates a strata of unsaturated valley-fill material which probably has never before been drained and which was originally deposited under water.

(2) The texture of soils underlying the affected area is extremely fine, consisting of horizons of clay and sandy clay with considerable colloidal material therewith. The area is located midway and farthest removed from the mouths of the perennial streams of the Tule River and the Kern River.

(3) During the past decade extensive geophysical exploration by means of deeply set explosive blasts has been made throughout the breadth and length of the Valley including this area in question. Serious damage to the irrigation-wells of certain landowners has resulted directly from these explorations.

(4) The Southern Pacific Railroad operates many heavily loaded trains every day throughout the length of the affected area and the vibration due to the train is felt through the ground for great distances away from the track.

In the light of these phenomena tentative explanations of the subsidence might be presented. The outstanding factor appears to be that the excessive lowering of the water-table in the fine-textured lacustrine soils has left an unbalanced static support under the 100-foot thick over-burden of surface-soils. When the deeper soils were saturated, the forces of surface-tension, cohesion, and buoyancy together with a certain amount of vertical uplift force against the upper impervious strata by artesian pressure all tended to support the surface of the land. But when as much as 60 feet to 100 feet of subsoil was left unsaturated, all of these forces were lessened or destroyed and any amount of ground-vibration would immediately cause settlement and compaction of the materials to a point where the supporting forces were again equal to the load. A natural compaction or settlement of from three per cent to five per cent in clay-soils from saturated to drained conditions has been repeatedly observed and allowed for in excavated and earth-filled structures.

There may be other areas within the San Joaquin Valley where subsidence has occurred but only by an extensive leveling-program can the matter be determined. Similar subsidence has occurred in the Santa Clara Valley in California, and this area has been described in previous papers before this Section. Other areas in the United States suffering subsidence are reported in various articles in engineering publications.

The effect of the subsidence in the Delano Area upon proposed major conveyance-works is not a serious matter but is one which can not well be lost sight of. The preliminary location of the Friant-Kern Canal passes through this area on the east side. Subsidence of two feet is observed along three or four miles of this location. If subsidence continues henceforth, it can be readily seen that a reversal of the designed flat gradient of the canal will occur in a very few years. The answer to the problem will, no doubt, be the provision of unusual canal free-board in the affected area.

Salt-concentration problem--It has been pointed out that there is no surface or subsurface outflow for any of the waters flowing into the San Joaquin Valley Basin south of the Kings River delta-ridge. The only means of water-dissipation is by means of evaporation and transpiration.

All waters, from whatever source, reaching this Upper San Joaquin Valley floor contain some soluble salts, and through periods of many years these salts have become so concentrated at certain places as to become injurious to plant-growth. Salt concentrations in the surface-soils are further increased by natural plant-growth and soil-oxidation processes and by artificial vertilization-activities. Oil-extractions from many areas throughout the Basin are increasingly contributing large quantities of saline solutions onto the adjacent land-surfaces. A large portion of surface-soil salts find their way into the ground-water underlying the cultivable land, and the extensive pumping of underground water brings these salts back onto the surface. It is to be expected, therefore, that during the next few years there will be a rapid acceleration in rate of salt concentration in the valley-soils and ground-water.

It is, therefore, believed to be incumbent upon the various agencies concerned with the prosperous continuance of agricultural enterprises in the Upper San Joaquin Valley to design and prosecute a plan in the very near future of drainage-facilities in order to maintain a balance in the salinity-concentrating processes being imposed upon this area.

State Division of Water Resources,
Sacramento, California

DISCUSSION

ALBERT W. PLUMMER (United States Engineers, Sacramento, California, communication of February 11, 1941)--The matter of "net use" or disappearance of water from irrigated areas is important and I would like to point out considerations which I feel should be understood so as to avoid obtaining values for "net use" without due regard to the influence of some of the important variables which Mr. Ingerson's method includes. In this connection, I believe that the variation of irrigated acreage within the boundaries of the water-unit is sometimes important enough to justify special attention. I will attempt to illustrate my point by presenting a hypothetical example of the derivation of "net use" in a manner similar to that presented by Mr. Ingerson and also by a slightly modified method, which might be an improvement. In this example water-supply, irrigated acreage, and ground-water elevation are considered as variable with the influence of all other factors considered as being constant. The influence of changing irrigated acreage can best be illustrated by adopting a precise value for "net use" and working backwards to check the adopted value.

Example--Given gross area of water-unit equals 100,000 acres and net importation of water, irrigated acreage, and change in ground-water level as shown in columns (1), (2), and (4) of Table 1, and assuming the precise value of "net use" is 2.00 acre-feet per acre, the replaceable voids represent ten per cent of the total soil-volume, hence 10,000 acre-feet contribution to the ground-water would result in a rise of one foot over the 100,000 acres within the water-unit.

Table 1--Basic groundwater data

Net Imported seasonal water-supply, acre-feet (1)	Irrigated area, acres (2)	Net Imported water-supply A F per irr. acre (3)	Mean Measured change in ground-water el. feet[a] (4)	Auxiliary columns		Modified change in ground-water el., feet[c] (7)
				Total net use[b], acre-feet (5)	Contribution to ground-water, acre-feet (6)	
340,000	85,000	4.0	17.0	170,000	170,000	20.0
297,500	85,000	3.5	12.75	170,000	127,500	15.0
280,000	80,000	3.5	12.0	160,000	120,000	15.0
200,000	80,000	2.5	4.0	160,000	40,000	5.0
90,000	60,000	1.5	- 3.0	120,000	- 30,000	- 5.0
50,000	50,000	1.0	- 5.0	100,000	- 50,000	-10.0

[a]Normally measured in field, but obtained by converting column (6) in this example so as to obtain precise value under base assumption used.

[b]Equals 2.0 acre-feet per irrigated acre, by assumption.

[c]Equals {column (4) [(Gross area of water-unit)/column (2)]}.

The two auxiliary columns were included in Table 1 to account for the total amount of the imported supply and to compute the theoretically precise change in ground-water depth which would normally be measured in the field. These auxiliary columns are not necessary in practical cases where ground-water change [column (4)] is measured in the field.

When the change in ground-water elevation [column (4)] is plotted against inflow per irrigated acre (see Figure A) and a straight line drawn through the plotted points, the value for "net use" comes out to be about 1.8 acre-feet per irrigated acre instead of the correct value of 2.0 which was the value upon which the ground-water changes were based. This difference of 10 per cent in the "net use" is due to the variation in irrigated acreage. However, by a slight modification in the method used this discrepancy can be eliminated and in addition a direct means obtained for determining the per cent of replaceable voids in the soil. The modified method theoretically considers all the imported water and ground-water fluctuations to be confined to the irrigated area. This is done by taking the measured mean change in ground-water level over the 100,000 acres comprising the gross area of the water-unit and multiplying the change by the ratio (gross area of water-unit)/(area irrigated) to obtain a modified change in ground-water fluctuation [column (7)]. These modified values are then plotted against the inflow per irrigated acre and, as can be seen from Figure A, they all fall in a straight line giving a "net use" of 2.0 acre-feet per acre which checks the adequacy of the modified method to correctly account for changes in irrigated acreage. In actual practice the plotted points used in the modi-

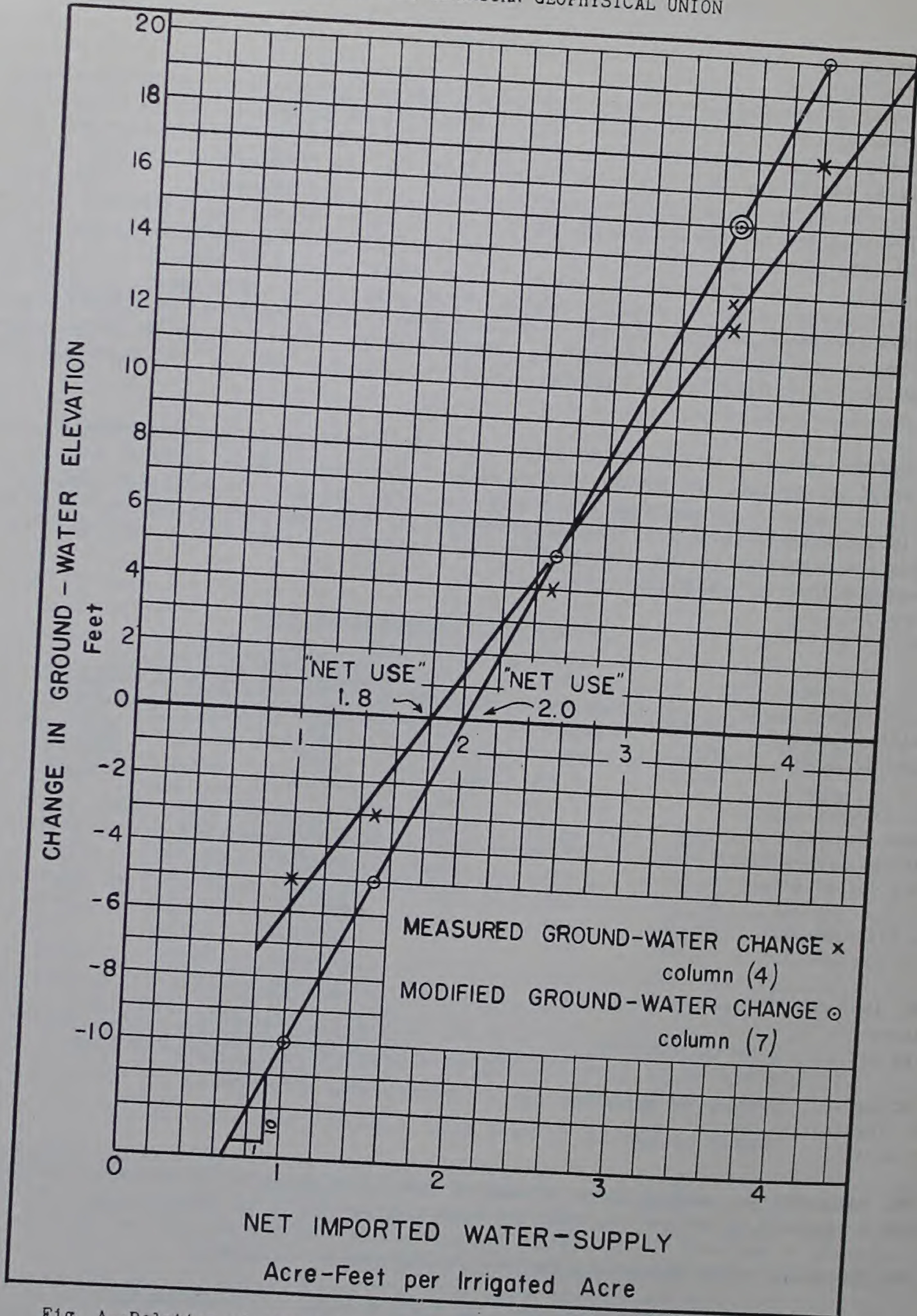


Fig. A--Relation of change in ground-water elevation to irrigation-use

fied method would deviate from a straight line because of differences in seasonal rainfall, "net use", and accuracy of field-measurements. These differences were not considered to exist in the theoretical example presented in order that the effect of a single variable, changing irrigated acreage, could be seen. The slope of the straight line in the modified method accurately represents the per cent of replaceable voids, or drainage-factor, which was assumed to be ten per cent in the example. The graph checks this as it indicates one acre-foot per acre contribution to the ground-water results in a rise of ten feet in the ground-water elevation when it is theoretically considered to be all confined under the area to which it was applied.

In most areas the change in irrigated acreage is small and would not appreciably affect the resulting value for "net use." However, in areas having large acreage, such as pasture-areas, which are not irrigated in seasons of deficient gravity water-supply or where the irrigated

acreage is expanding rapidly, I believe the change may have appreciable effect on the derivation of a value for "net use." I agree with Mr. Ingerson that the accuracy of the basic measurements as well as other influencing factors offer definite restrictions to the accuracy attainable for work of this nature and would not justify extensive effort to refine the method used, but the simple process of computing a theoretically modified ground-water fluctuation [similar to column (7) of Table 1] against which to plot the unit-inflow might be justified.

ALBERT W. PLUMMER--In the determination of net use, what correction is required for changes in acreages? In irrigated acreage what about changes--what, if any, influence in the method of use?

MR. INGERSON--Naturally, the results of this method of analysis would only be more accurate if the irrigated area was uniform each year. The acreage irrigated is a factor in this analysis but the annual changes do not substantially change the result inasmuch as many other factors are involved.

MR. PLUMMER--For the example presented in your paper, has any value been computed for the per cent error the changing irrigated acreage might produce?

MR. INGERSON--It is said that the engineering profession is a science that speaks in terms of accuracy and not correctness. One is always accurate but not always correct. In ground-water units where the annual irrigated area is dependent upon the water-supply errors in the results of this analysis are negligible; and where there has been a steady increase or decrease of area in any unit regardless of the available water-supply the error may be as much as 10 to 20 per cent.

MR. PLUMMER--The way I figure, a change of 15 per cent in the irrigated acreage would result in a variation of about 15 per cent in the ground-water fluctuation when the same unit water-supply per irrigated acre was obtained.

MR. INGERSON--The measurement of inflow into any unit cannot always be carried out accurately. There is always a question as to just what that inflow is, when it is realized that rainfall-penetration, flat-surface runoff, lateral ground-water movements, and variable plant-transpirations are definite factors but of relatively immeasurable dimensions.

L. STANDISH HALL (Hydraulic Engineer, East Bay Municipal Utility District, Oakland, California)--You have a basin where you can measure inflow and outflow?

MR. INGERSON--The ground-water units chosen serve as a "basin", into and out of which flows are determined as accurately as possible. If it were a closed basin the degree of accuracy would be better.

GEORGE W. TRAUGER (Lindsay-Strathmore Irrigation District, Lindsay, California)--I want to ask Mr. Ingerson if the Lindsay-Strathmore Area is still high man as to depth of the underground water-table.

MR. INGERSON--The water-table is about 200 feet below surface. No other area is as low but you have a teammate. That is the Earlimart-Delano District.

MR. TRAUGER--I am glad of that. We are still high man.

C. H. LEE (Consulting Hydraulic Engineer, San Francisco, California)--I would like to ask Mr. Ingerson regarding the boundaries of the unit. Is it a geological line or a practical unit?

MR. INGERSON--It is a practical line in the sense that we take into account the geology and the surface-topography, the irrigated areas that might be in a group created by a single source of supply, and lastly, the extent of service of the water-supply itself.

DRAINAGE IN THE SAN JOAQUIN VALLEY AS IT MAY BE AFFECTED BY THE CENTRAL VALLEY PROJECT

Walter W. Weir

Drainage-conditions as we find them today, in the San Joaquin Valley, are largely man-made. Without attempting to go into detail, or, in fact, even to verify this statement from historical records, it would appear logical to believe that the only primeval need for drainage in the

Valley was confined to its flatter portions which were overflowed during the spring and early summer. Our characteristic two-season climate would limit overflow to periods of heavy rains from January to March and to the first few hot days of early summer when the accumulated snows were melting rapidly. Probably the only permanently swampy areas were the Delta country at the confluence of the San Joaquin and Sacramento rivers where the influence of tidal action was more dominant than the flood-stage of the streams and the Tulare and Buena Vista Lake areas of Kings and Kern counties. Overflowed areas along the San Joaquin from Mendota to the delta I have not considered as permanently wet as they probably dried up completely during the late summer and fall.

With introduction of irrigation to the Valley, the diversion of water from its natural courses and its distribution over what would normally be dry lands, at unseasonable (from the natural concept) times, man has produced a condition which nature never intended. (I am not condemning this practice, just calling attention to it.)

In all arid regions (the San Joaquin Valley most of which has a rainfall of ten inches or less must be so classed) the presence of alkali salts in the soil is a natural phenomena and whenever, through irrigation, the water-table rises near enough to the surface for capillary movement to the surface there is almost sure to be a surface-accumulation of salts.

In looking over some of the older literature [see "References" 1 and 2 at end of paper] on the subject of drainage in the San Joaquin Valley I find particular reference to conditions about Fresno, as for instance, "In 1873 when irrigation-water was first taken from Kings River the water-table was 65 feet deep but in 1878, after five years of irrigation, water stood at six feet from the surface of the soil." Again I find such interesting statements as this: "In 1888 on the white-ash lands the water-table fluctuated between two and three feet from the surface in the spring growing season and eight to ten feet in the winter season."

In another place I find the following: "Before canals covered the Fresno plains with water the water-table was more than 30 feet below the surface. Excessive irrigation soon filled the substrata, then the subsoil and later the soil to within two to three feet of the surface, causing great destruction of orchards and vineyards over a large area."

Notwithstanding some efforts at reclamation through drainage, apparently conditions continued to grow worse until about 1915 or 1916. I first became personally acquainted with this part of the State in 1914 and by that time no less than 80,000 acres in Fresno County alone had deteriorated from vineyards and orchards through stages of alfalfa and grain-hay, to Bermuda grass pasture. Similar conditions existed in Stanislaus County and also in Kern and Kings counties.

I believe it was in 1919 that experiments in drainage by pumping from deep wells were extensively undertaken in the Salt River Valley of Arizona. This type of drainage proved so successful that by 1925 there were several hundred wells on the east side of the San Joaquin Valley between Manteca and Fresno. It was soon learned that water so pumped was a valuable addition to the irrigation-supply and since then there has been such a general and widespread expansion in the number of pumping plants that it is almost safe to say that today there is no serious drainage-problem in the Valley. It should be remembered, however, that the extensive pumping in the San Joaquin Valley does not now have drainage as its primary purpose. A series of dry years and shortage of gravity-water has made pumping an important source of water almost everywhere and in some places the exclusive source.

Although pumping from deep wells has been eminently successful in lowering the water-table in high water-table areas, I am quite firmly of the opinion that unless the water so pumped had been found valuable as a supplemental irrigation-supply that the drainage-problem could not have been so completely solved. To my mind this is such an important consideration that it will bear further emphasis. Drainage by pumping from deep wells will be successful only if the water is so badly needed that it has a real value for irrigation. Stated in another way: Any area which has all of the gravity-water it needs has too much.

This is clearly shown in two areas, one around Hanford in Kings County, and the other at Los Banos and Gustine in western Fresno County, these being the only areas in the Valley now having, what the local people consider as an adequate supply, and the only areas which now have a really serious drainage-problem.

Up to this point I have been attempting, briefly, to set up a background for the subject I was asked to discuss, namely, "Drainage in the San Joaquin Valley as it may be affected by the Central Valley Project."

Let us start at the lower end of the Valley and take up the several sections as we come to them, and see what may happen, if history follows the usual course of repeating itself.

The Delta Country--The proposal here is to provide fresh water from Shasta Dam down the Sacramento River in sufficient quantity to hold back the brackish water of the Bay and lengthen the irrigation-season. In all probability this will have very little effect upon drainage-conditions in the Delta. You are probably all familiar with the fact that the Delta lands are irrigated by syphoning water over the levees from the surrounding sloughs, then collecting the drainage-water in open ditches from which it is pumped back over the levees. The new set-up will probably not alter this procedure but will simply provide a better quality of water and a lessened likelihood of injury to crops from the use of brackish water.

The greatest single problem of the Delta area is one of subsidence. The whole area is gradually but consistently subsiding as the result of tillage and other farm practices. Fires, usually intentionally set, may lower the ground-surface as much as six inches in a single season.

Twenty years of systematic measurements of subsidence on Lower Jones, Mildred, and Bacon islands shows that the surface of these islands is more than 40 inches lower than it was when they were first put into cultivation. Subsidence also increases the salinity of the soils as most of the soluble salts remain in the ash after fires or from normal oxidation and compaction. The use of less saline waters for irrigation should, if there is any change whatever, be for the improvement of conditions, although the cost of drainage-pumping will increase somewhat as the differential in water-level inside and outside the levees increases.

Contra Costa County--Drainage is almost certain to become a problem on lands under the Contra Costa Canal. For the most part this area has not heretofore been irrigated. Except in the vicinity of Oakley the soils are relatively heavy and impervious. The use of irrigation, and especially gravity-irrigation, on lands already in cultivation introduces a convenience into a community with which it has had no experience and not until after many farms have been ruined will the farmer learn how much water to apply and when to apply it. The heavy texture of most of the soils in the Concord section and the clay-subsoil in the soils along the bay shore between Antioch and Port Chicago provide ideal conditions for over-irrigation. This area should be watched very carefully for signs of water-logging but one will probably have to wait until water-logging actually occurs before any remedies can be suggested.

Valley-trough from Mendota to the Delta--Friant Dam provides storage on the last of the streams entering this area and flood-conditions should be materially improved even to the point of making possible the reclamation of some lands along the lower San Joaquin which have not been used because of overflow. On the other hand, the removal of overflow from some of the heavy textured soils along the west side of the Valley may cause them to become more saline and less valuable for pasture than they are under present wet conditions.

Western Fresno County--Eventually water may be delivered to the west side, in Fresno and Merced counties high enough to irrigate all the lands below the 400-foot contour. If and when this is done there will be a considerable area of good land come into high production that is now either dry-farmed or irrigated from wells. In those lands lying above the present gravity-systems, the water-table is low and it will probably be a long time before any serious damage will result from its irrigation. I would expect to find almost complete abandonment of pumping in this area when gravity-water is available, as pumping costs are high and the quality of the water is poor. Well-water in this section contains boron as well as other salts, and the continued use of these bad waters may become serious even though there is no drainage-problem.

Those lands which lie below the present gravity-system and above the overflow-area are, even now, somewhat water-logged, are alkaline, and some of them are in need of drainage. It is easily conceivable that a very little more water, such as might come as waste from higher lands, would be enough to definitely put this area on the wrong side of the ledger as far as drainage is concerned. A large part of this area which is now devoted to alfalfa, cotton, melons, asparagus, and similar crops may have to be given over to permanent pasture for dairy cattle. This is not necessarily an undesirable prospect for the Valley as a whole but it may work a hardship on some individuals.

Madera and Fresno counties--The east side of the Valley especially in Madera and Fresno counties presents a different picture and as I see it, one in which there is considerable potential danger. I may be criticized for taking such a pessimistic attitude but my 26 years of experience with drainage-problems in and about Fresno and 35 years of irrigation-history back of that, cannot be entirely disregarded. Generally speaking there is no shortage of water in these

areas. Nearly all of the good soils in these areas, soils that are really fit to be irrigated, have all the water they need. As I have already mentioned the water-table was at one time much higher in the Fresno Area than it is now. This lowering was due primarily to the necessity for pumping during the later part of the season. We all know that there has been a below-normal cycle in rainfall, and we may still be in it, but with a return to normal or above normal rainfall there is certain to be less need for pumping and a corresponding rise in the water-table. This was demonstrated very clearly in 1937 and 1938 when there was sufficient runoff from the upper Kings River Watershed to put water into Tulare Lake. The water-table rose rapidly over the major portion of the Fresno Irrigation District. In one season the water-table rose as much as six to eight feet bringing it again within capillary rise of the surface. The most startling thing about the whole situation was that a majority of the farmers thought that it was a good thing. Fortunately, there was the usual late-season shortage and this rise in water-table did no permanent damage, but one can imagine what will happen when there is stored water available for later summer and fall irrigation.

Although it has been fully demonstrated that a high water-table in the San Joaquin Valley can be effectively lowered by pumping it is extremely difficult to "put over" a program of pumping for drainage alone. Some use must be made of the water and this use must be born of necessity. Even cheap power is not incentive enough to deliberately waste pumped water.

In Madera County there has been a determined effort to get additional water from Friant to use on new land or land now supplied solely with pumped water. There is not very much good land in Madera County which does not now have adequate water. The hard-pan lands of that County, and other counties as well, are better off without water or with only a limited supply of water. If water is cheap, hard-pan lands are almost certain to be over-irrigated. Briefly, the salvation of Fresno and Madera counties has been their shortage of later-season water and anything that brings about a material change in this will bring with it a high water-table and a return of the days of 1914 and 1916 when lack of drainage came very near to ruining the whole country.

Tulare County--Tulare County has always depended very largely on pumped water and there has not been enough for all the better lands. Locally some drainage-trouble may develop but I do not look for any widespread difficulties unless irrigation is extended to the hard-pan lands. Down on the lower end of the County, next to the Kings County line, a considerable portion of the area contains alkali in dangerous quantities and a little more or less water will not make much difference. This section is already so bad that there has been a determined effort on the part of the Central Valley Authority to keep it from getting more water, realizing that much of it is not fit for irrigation and if irrigated might be subject to unwise exploitation and financial ruin for whoever happened to be left holding the title. There is not enough water for all of the good land in the upper end of the Valley and it would be a crime to give any additional water to these alkali areas.

Kings County--In Kings County drainage is now a very serious problem. As I have already pointed out this is one of the few areas that even the dry years has not cleared up. As I see the situation Kings County people have been very reluctant to admit any poor drainage-condition. They seem to be afraid that the people in the Fresno Irrigation District would consider it as an indication that there was more water going to Kings County than they needed and would take a little more of the Kings River flow. Any more water than it now has will completely ruin Kings County. On the other hand, if these people are assured, through the Central Valley Project, that the upper Kings River users do not want any of the water that Kings County is legally entitled to, it may make them willing to admit that they have a drainage-problem and do something about it. There seems to be a sort of "dog-in-the-manger" attitude between these two communities.

Kern County--In Kern County the best soils are to be found well above the proposed location of the Friant-Kern Canal and will therefore not be subjected to high seepage-losses. The situation is similar to that already described for western Fresno County except that because of somewhat better quality of the well-water they can continue to use it without injury to their soils.

For these lands above the gravity-flow of the proposed new canal there is not likely to be much trouble. These areas have low water-tables, natural drainage is good and the pumping lift will continue to be so high that the cost of pumping will tend to prevent any serious rise in the water-table.

On the other hand, much of the land along the lower Kern River is already poorly drained and saline and the addition of late-season gravity-water may have the effect of raising the water-table still higher and increasing the surface-accumulations to alkali salts unless pumping becomes a definite part of the program.

Drainage-conditions in this area have improved considerably during recent years for the same reason that they improved in Fresno County, namely, a series of dry years has forced the installation of hundreds of pumping plants. If for any reason there is sufficient gravity-water without using the pumps there will certainly be a rise in the water-table. Practically no provision has been made for drainage in this area other than the pumps. The same question arises here that was raised for Fresno County. Will farmers continue to use their pumps solely for drainage, when gravity irrigation-water is available in sufficient quantity for their needs?

Merced-Turlock-Modesto Area--Going back down the Valley for a moment to Merced, Turlock, and Modesto, it is noted that these areas also have suffered from poor drainage in the past and this section has spent more on drainage-works than all the remainder of the Valley but it was not until pumps were installed to lower the water-table that any material benefit was derived from their drainage-efforts. Here, as elsewhere in the Valley, shortage of late-season water forced the operation of the pumps for irrigation and then they began to really function. Fortunately these districts found that pumped water was as good, and as cheap, as their stored water. My information is that these areas are not to be supplied with any Central Valley Project water and that they will go on in about the same way as at present with drainage pretty much in the background at this time.

Summary--Summarizing briefly, I anticipate one entirely new drainage-problem to arise from the operation of the Central Valley Project, this being the one in Contra Costa County. Elsewhere old drainage-situations, now partially alleviated by extensive pumping, will be aggravated to the point where they will again become serious. New lands, or lands heretofore dependent solely on pumped water, will be safe under any normal procedure. The whole drainage-problem, however, could be solved by everywhere withholding late-season gravity-water to the extent that 25 or 30 per cent of the annual requirement be pumped from deep wells.

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SESSION, AFTERNOON OF JANUARY 16, 1941--MEMORIAL AUDITORIUM
CHAIRMAN, S. B. MORRIS

INTRODUCTORY DISCUSSION AND COMMENTS ON THE FOUR PAPERS BY CHARLES H. LEE, GEORGE HARDMAN AND CRUZ VENSTROM, P. B. ROWE, AND J. BJERKNES

Charles J. Kraebel

These four papers, of such wide range and significance, present important aspects of rainfall and runoff and go back to the fundamentals of various hydrologic problems of the Sierra Nevada and Southern California mountains. They should provoke lively discussion.

Mr. Lee, active for many years in the accumulation and analysis of the precipitation-records, at previous meetings has given us progress-reports on this work. His tabulations show that the runoff for the San Joaquin River in 1881-82 was equal to the precipitation and in 1910-11 was slightly greater. This appears to indicate a building up of soil-moisture and snow during wet years and the possibility of an appreciable carry-over of precipitation-runoff from wet to dry years. Important also, it seems to me, is the showing of the possibility of estimating the available water that might be expected from the Sierra Nevada during wet and dry periods and the amount of water to be handled in time of flood-years. Such estimates are essential in watershed-management which must be directed in large part toward finding ways and means of saving water in years of abundance for use during years of deficiency.

Mr. Hardman shows that Pyramid Lake, which is the ultimate recipient of the waters of the Truckee River, has something less than a hundred years remaining of existence as a lake. Community interest no doubt demands that the irrigation of hundreds of acres of agricultural land along the River and at Fallon is a more important use of these waters than the maintenance of the lake itself.

Mr. Rowe details the results of nine years' study of factors of the hydrology of the Sierra Nevada foothills. His complete report has been submitted for publication as a technical bulletin of the United States Department of Agriculture. Generally speaking, the paper is of value to us in two important respects: (1) It represents a sound approach to water-cycle studies in that it seeks to isolate and evaluate the influences of individual factors of the problem, a knowledge of which is prerequisite to good watershed-management; (2) the study indicates that through land-management, that is, manipulation of the vegetation on the land-surface, we can exercise a considerable degree of control over erosion and floods, and over the production of usable water. All of this has an important tie-in with the discussions in this morning's program on the problems of importing water into the San Joaquin Valley.

The paper by Prof. J. Bjerknes, presented by Mr. Paulson in the former's absence, is difficult for an audience to follow and fully absorb. It develops a plausible case for possible occurrence of rain-storms much more severe than any thus far recorded in southern California. The possibility, however remote, of the occurrence of rain at the rate of three inches per hour for several hours in the San Gabriel Mountains, gives a perspective against which plans for flood-control and storm-drainage in the south coastal basin can be more intelligently made.

The purpose of the Flood-Control Surveys by the Department of Agriculture under the Flood-Control Act of June 28, 1936, is to collect information needed to plan and execute action programs of "runoff and water-flow retardation and soil-erosion prevention" in designated watersheds which have serious flood-problems. Information obtained from investigative work reported this afternoon is much needed to determine potential storm- and flood-hazards and to evaluate benefits to be expected from wise watershed-management.

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TOTAL EVAPORATION FOR SIERRA NEVADA WATERSHEDS BY THE METHOD OF PRECIPITATION AND RUNOFF DIFFERENCES

Charles H. Lee

Total evaporation as used in this paper, is the sum of all water-losses to the atmosphere from a stream drainage-basin, during the annual climatic cycle. It occurs principally as evaporation from water-surfaces, moist soil, and snow, as transpiration from vegetation, and as interception. It is quantitatively represented by annual precipitation upon the watershed minus runoff, corrected for change in storage within the watershed and for subsurface leakage. Various

terms for this quantity are used in literature such as evapo-transpiration, fly-off, natural water-loss, etc. In view of the growing interest in the determination of water-losses, hydrologists will doubtless before long unite in selecting a single appropriate term.

The individual elements which contribute to the total evaporation from a watershed are all controlled by the evaporivity of the atmosphere in contact with the ground-surface. Evaporivity thus controls the variations in total evaporation during any given period of time and establishes for it a maximum limit. The measure of evaporivity in humid regions is the rate of atmospheric evaporation from a large free surface of fresh water. In semi-arid and arid regions insufficient precipitation may occur in certain years to supply the needs of vegetation. Under such conditions the annual precipitation instead of evaporivity establishes the limit for total evaporation, except as natural conditions are modified by irrigated agriculture.

The actual total evaporation during any period of time never attains the maximum, being controlled by the opportunity for evaporation which is afforded by the watershed. Evaporation opportunity varies with the aerial extent of water, snow or growing vegetation upon the ground-surface, the type of vegetation, and with the degree of moisture in the soil. Evaporation-opportunity varies from month to month and year to year, following the annual climatic cycle and the more or less cyclic secular variation in precipitation.

A fundamental characteristic of total evaporation is its constancy in amount and the relatively narrow range of annual variation in comparison with precipitation and runoff. The reason for this characteristic is to be found in the stability of the factors which control it. Among these, evaporitivity is the basic factor and experiences little change from year to year largely because of the limited variation in annual air-temperature and humidity over any given area. The elements which control evaporation-opportunity are also constant, or, at least, subject to very slow natural change. The exception is precipitation and the frequency, intensity, and duration of storms. Where precipitation is sufficient for the needs of vegetation, however, and occurs during the winter season even this is of minor consequence. More important exceptions are artificial changes such as extensive denudation of vegetal cover by fire or deforestation, or the introduction of agriculture.

The constancy of total evaporation is an important aid to its determination, since runoff is the residual of precipitation after deduction of water-losses. This fact has been recognized by hydraulic engineers for many years, and in humid regions has been utilized for the computation of water-supply available from stream-flow [see 1, 2, 3, 4, 5 of "References" at end of paper]. Much information is available in engineering literature as a basis for the quantitative determination of total evaporation by difference.

The essential relation for such determinations for a given drainage-basin and period of time is the equation

$$E = (P - R \pm S - L)$$

where E = total evaporation, P = precipitation, R = runoff, S = storage-correction, and L = watershed-leakage, all expressed in inches of depth upon the area of drainage-basin. In practice, watershed-leakage is usually negligible, the important exceptions occurring in watersheds underlaid by limestone or gypsum. Water in storage in the watershed on the other hand, represents an important correction and one difficult of determination. The use of the water-year ending September 30 simplifies computations to a certain degree, since at that date a smaller quantity of water is held in storage in lakes, in ground-water as soil-moisture, or as snow, than at any other time of the year. The averaging of annual precipitation and runoff by groups of years also helps to eliminate the effect of the carry-over from one year to the next. Periods of three or five years are preferable for this purpose. The average difference of annual precipitation and runoff over a period of 15 years or more equalizes storage and closely represents total evaporation for a watershed.

In application of the method by difference, it is essential that depth of precipitation be representative of the watershed as a whole. With flat topography this is attainable if precipitation-stations are well distributed geographically. In hilly and mountainous regions it is more important that they be well distributed in altitude so as to compensate for the variation of precipitation with altitude. The scarcity of precipitation-records in mountainous regions, however, has discouraged the use of the method in such areas [5]. This paper endeavors to fill this gap and describes a method for applying the method to mountainous watersheds.

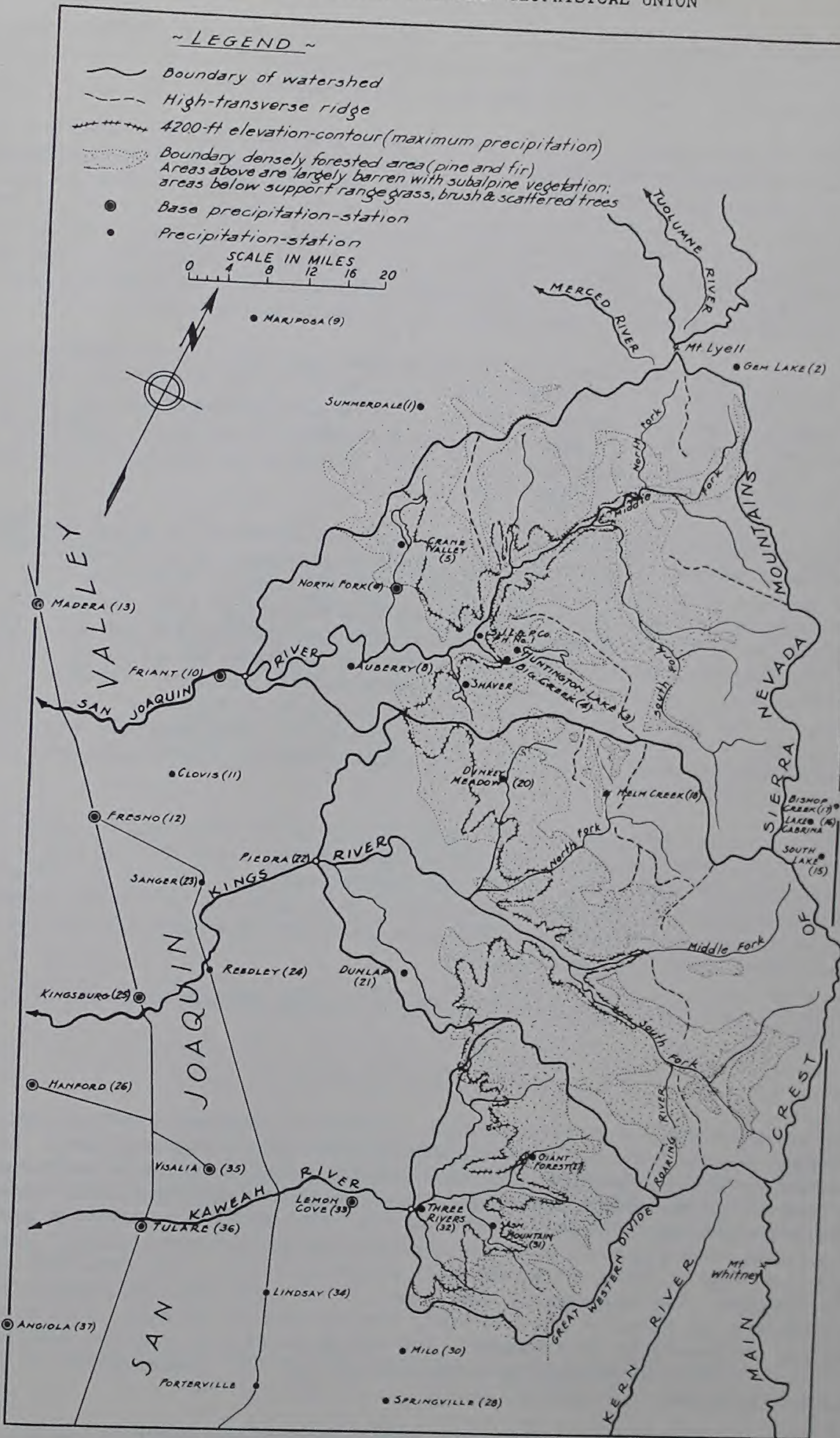

Fig. 1--Map of San Joaquin, Kings, and Kaweah River watersheds

Selected watersheds

Three adjacent watersheds were chosen for illustration of the method, namely, those of San Joaquin, Kings, and Kaweah rivers (Fig. 1). These streams are typical of the western slope of the Southern Sierra Nevada Mountains, their measured flow is the least affected by diversion and artificial over-year storage, stream-gagings are available over a period of nearly 40 years, and

Table 1--Physical characteristics of watersheds of selected streams, western slope of Sierra Nevada Mountains

Stream	Watershed area, sq mi	Elevation in feet of			Vegetal cover in per cent of area		
		Stream-gaging station	Sierra crest	Average	Range grass, brush, scattered trees[a]	Dense forest, pine and fir[b]	Scattered forest[c]
San Joaquin	1632	350	10,000-13,000	6885	17	39	44
Kings	1694	550	13,000	6550	22	37	41
Kaweah	520	750	13,000	5800	35	48	17

[a]Foothill and lower canyon-bottoms. [b]Intermediate slopes including zone of maximum precipitation. [c]Intermediate and culminating ridges, higher slopes and basins, largely barren and subalpine.

a considerable number of precipitation-records are available at high elevation. The physical characteristics of these watersheds are shown on Table 1. San Joaquin and Kings River watersheds are similar as to area, elevation, vegetal cover, and geology. They extend back to the main crest of the Sierra at elevations from 1000 to 13,000 feet with considerable portions at high elevation supporting either a sparse sub-alpine vegetation or barren. The intermediate zone of elevation is heavily forested with pine and fir. The lower levels are covered with range-grass, brush, and scattered trees. Kaweah Watershed, although attaining an elevation of 13,000 feet, extends only to the Great Western Divide. Instead of over 40 per cent, only 17 per cent is high and barren. The heavily forested zone covers almost 50 per cent of the Watershed instead of less than 40 per cent, the foothills 35 per cent, instead of 20 per cent. Geologically the sedimentary rocks are more in evidence than in the watersheds of the other two streams where granite predominates. Conditions on the Kaweah thus favor a higher quantity for total evaporation.

Relation of precipitation and elevation

The basis of the method for computing total evaporation from mountain watersheds is the precipitation-elevation diagram. This represents the relation of precipitation to elevation within the watershed. Given such a diagram and a topographic map of the watershed, isohyetal lines can be drawn with reasonable accuracy provided certain fundamental principles are observed.

Change in depth of precipitation with elevation arises from temperature-change in horizontally moving air-masses, as these air-masses undergo adiabatic expansion or contraction with vertical displacement induced by topographic slopes interposed across the direction of movement. An ascending slope presented to the prevailing direction of storm-movement receives increasing precipitation up to an elevation of from 4000 to 6000 feet, above which level there is a decrease up to elevation 15,000 feet. Above this level another cycle of increasing and decreasing precipitation occurs. If the maximum elevation of the slope is a sharp crest at an elevation lower than the critical elevation the increase or decrease in precipitation ceases abruptly at the crest. On a reverse slope beyond a crest, precipitation decreases with decrease in elevation. The degree of inclination of the slope, whether windward or leeward, is a controlling factor in the rate of change of precipitation with elevation. As the opposite slopes of mountain ranges seldom have the same inclination, it follows that rates of change differ and that equal precipitation does not occur at the same elevation on the two slopes.

If the surface beyond the crest of an ascending, or base of a descending, slope is generally level, precipitation over it varies but little from that at the break in slope, except as influenced by other phenomena. Air-masses moving over such a surface upon entering a second mountain range undergo the same adiabatic expansion and contraction with similar results. If the first range is relatively high and no active source of vapor intervenes, the depth of precipitation upon the second range at the same elevation will be appreciably less than upon the first range. Another set of precipitation-elevation diagrams are thus required.

Special conditions occur for isolated mountain masses and for major gaps or passes through mountain ranges. A mountain peak or short ridge casts a distinct rainfall shadow to leeward. Leeward of a gap, however, is a fan-shaped area of intensified precipitation, fading out if the

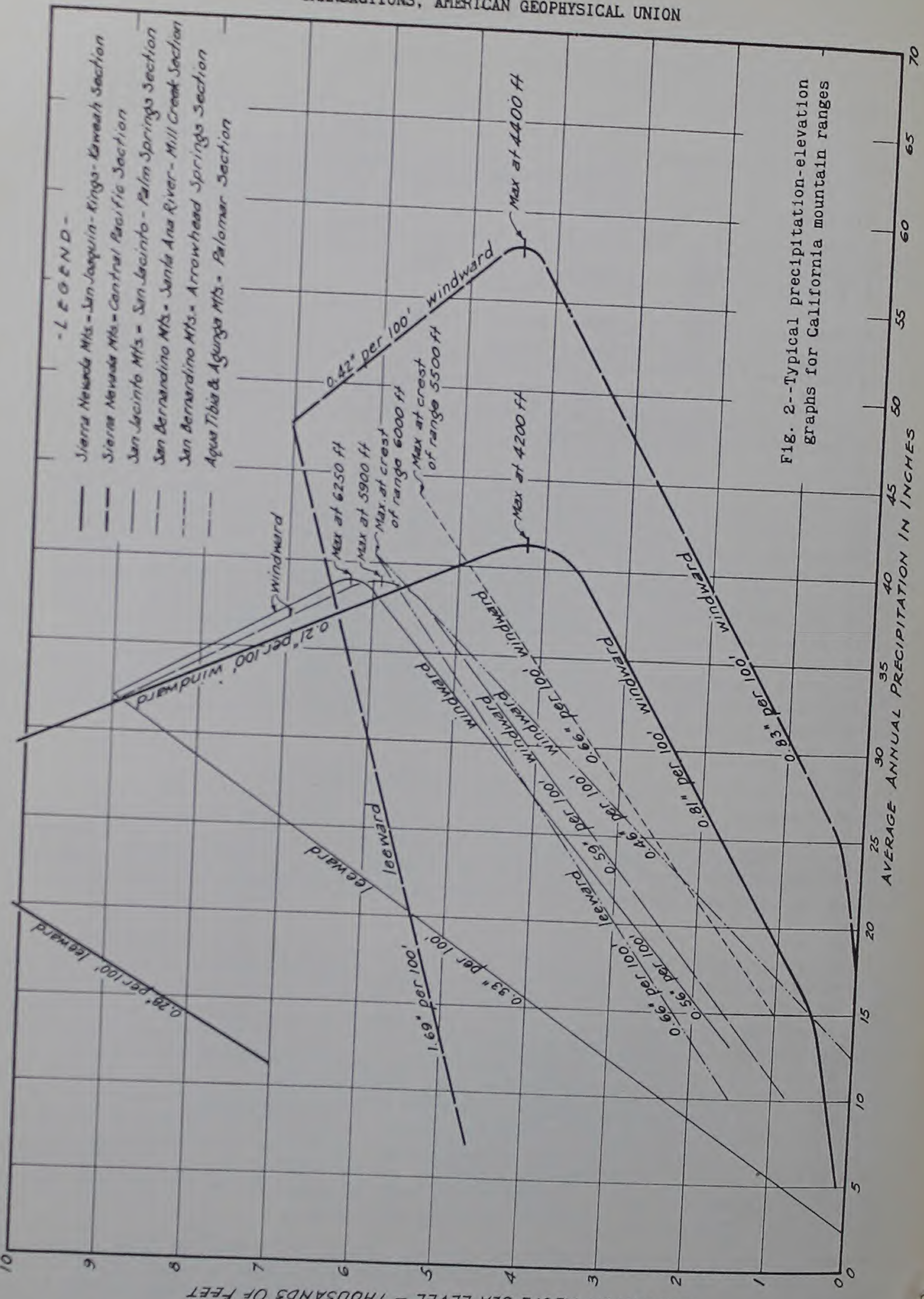

Fig. 2--Typical precipitation-elevation graphs for California mountain ranges

general slope is level or descending, increasing if the slope continues to rise.

Graphs illustrating typical variation of precipitation with elevation are shown on Figure 2. These graphs have each been prepared from adjusted long-term precipitation records at stations well distributed vertically and located in the vicinity of sections crossing the indicated mountain ranges at right-angles to the axial trend. The two sections across the Sierra Nevada Mountains have a rate of increase in precipitation on the windward slopes of 0.80 inch per 100

Table 2--Description of precipitation-stations

No.	Station	Watershed	Elevation, feet	Period record	Length record, years	Average record precipitation, inches	Per cent of 60-year average	Average 60-year precipitation, inches
1	Summerdale	Merced	5270	1896-1912	16	54.55	100	55.6
2	Gem Lake	Rush	9120	1925-1940	15	24.80	101	24.5
3	Huntington Lake	San Joaquin	7000	1915-1940	25	29.40	98	30.0
4	Big Creek	San Joaquin	4928	1915-1940	25	29.90	98	30.5
5	Crane Valley	San Joaquin	3500	1903-1921	18	52.23	102	51.1
6	North Fork[a]	San Joaquin	3000	1904-1940	36	33.20	101	32.9
7	S.J.L.and P.S. P.H. No. 1	San Joaquin	2441	1903-1919	16	26.82	103.3	26.0
8	Auberry	San Joaquin	2065	1915-1940	24	23.65	96	24.6
9	Mariposa	San Joaquin	1800	1908-1930	22	28.08	94.2	29.8
10	Friant[a]	San Joaquin	450	1897-1940	40	12.94	98	13.2
11	Clovis	Valley	400	1917-1940	23	12.36	97	12.7
12	Fresno[a]	Valley	293	1880-1940	60	9.48	100	9.5
13	Madera[a]	Valley	296	1899-1940	41	9.82	100	9.8
14	Mendota	Valley	177	1894-1908	14	6.46	100	6.5
15	South Lake	Bishop Creek	9620	1925-1940	15	18.10	101	17.9
16	Lake Sabrina	Bishop Creek	9100	1925-1940	15	18.10	101	17.9
17	Bishop Creek	Bishop Creek	8390	1911-1940	27	14.48	95.8	15.1
18	Helm Creek	Kings	8020	1921-1928	8	35.60	90	39.5
19	Cliff Camp	Kings	6150	1922-1940	18	36.40	98	37.1
20	Dinkey Meadow	Kings	5440	1922-1935	13	34.20	88	38.9
21	Dunlap	Kings	2800	1912-1916	4	29.33	112	26.2
22	Piedra	Kings	510	1918-1940	22	16.75	98	17.1
23	Sanger	Valley	371	1889-1915	26	10.90	101	10.8
24	Reedley	Valley	347	1899-1923	24	11.92	102	11.7
25	Kingsburg[a]	Valley	309	1880-1899 1906-1918	31	8.69	102	8.5
26	Hanford[a]	Valley	249	1899-1940	41	8.61	102	8.4
27	Giant Forest	Kaweah	6360	1921-1940	19	41.40	99	41.8
28	Springville	Tule	4050	1907-1940	33	35.10	98.5	35.7
29	Tule River	Tule	2500	1913-1921	8	37.84	100	37.8
30	Milo	Tule	1600	1898-1922	24	22.10	101	21.9
31	Ash Mountain	Kaweah	1600	1925-1940	15	26.32	101	26.0
32	Three Rivers	Kaweah	840	1909-1940	31	19.57	98	20.0
33	Lemon Cove[a]	Kaweah	600	1899-1940	41	14.62	100	14.6
34	Lindsay	Valley	384	1914-1940	26	10.80	99	10.9
35	Visalia[a]	Valley	334	1880-1940	58	9.83	100	9.8
36	Tulare[a]	Valley	289	1880-1914	34	8.68	99	8.8
37	Angiola[a]	Valley	208	1899-1940	41	7.35	100	7.4

[a]Base-station.

feet to elevation 4300 feet, above which the rate decreases to the crest of the range at rates of 0.20 and 0.40 inch per 100 feet, respectively.

The four sections across Southern California mountain ranges have rates of increase up the windward slopes of from 0.46 to 0.66 inch per 100 feet, attaining maximum precipitation at 6000 feet. Where the ranges reach to higher elevations the rates of decrease above this level are between 0.20 and 0.30 inch per 100 feet.

Rates on leeward slopes vary widely between the limits of 0.33 and 1.69 inches per 100 feet.

Diagrams have differing form depending upon the height of the mountain crest with reference to the elevation of maximum precipitation. The complete diagram, which is characteristic of the higher mountain ranges, has three arms, two on the windward slope and one on the leeward. This is illustrated by the two Sierra Nevada and the San Jacinto sections (Fig. 2). On the diagram for lower ranges, with crest-elevation at or below the elevation of maximum precipitation, the arm of decreasing rate on the windward slope is absent, as illustrated by the Agua Tibia and Agunga Mountain section.

Table 3--Records of precipitation at base-stations and indices of seasonal wetness, 1880 to 1940

Season	Fresno		Friant		North Fork		Madera		Kingsburg		Hanford		Visalia		Tulare		Angiola		Lemon Cove		Regional index of seasonal wetness
	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	
1880-81	8.22	87	.....	...	.....	...	.....	...	9.49	109	.....	...	11.67	119	9.98	113	.....	...	.....	...	107
1881-82	5.30	56	.....	...	.....	...	.....	...	4.74	54	.....	...	6.76	69	4.71	54	.....	...	.....	...	58
1882-83	7.16	76	.....	...	.....	...	.....	...	5.84	67	.....	...	6.58	67	6.07	70	.....	...	.....	...	70
1883-84	15.87	167	.....	...	.....	...	.....	...	15.85	182	.....	...	15.65	159	11.65	134	.....	...	.....	...	160
1884-85	6.65	70	.....	...	.....	...	.....	...	7.32	84	.....	...	7.75	79	5.56	64	.....	...	.....	...	74
1885-86	16.62	175	.....	...	.....	...	.....	...	14.53	167	.....	...	13.10	133	9.25	107	.....	...	.....	...	145
1886-87	7.41	78	.....	...	.....	...	.....	...	6.70	77	.....	...	.....	...	6.06	70	.....	...	.....	...	75
1887-88	6.73	71	.....	...	.....	...	.....	...	6.27	72	.....	...	.....	...	6.27	72	.....	...	.....	...	72
1888-89	7.99	84	.....	...	.....	...	.....	...	7.80	90	.....	...	10.67	108	7.55	87	.....	...	.....	...	92
1889-90	13.01	137	.....	...	.....	...	.....	...	14.41	166	.....	...	14.22	144	11.92	137	.....	...	.....	...	146
1890-91	8.25	87	.....	...	.....	...	.....	...	5.87	68	.....	...	9.15	93	6.77	78	.....	...	.....	...	82
1891-92	9.93	105	.....	...	.....	...	.....	...	8.63	99	.....	...	12.31	125	7.88	91	.....	...	.....	...	105
1892-93	11.10	117	.....	...	.....	...	.....	...	8.95	103	.....	...	10.27	104	6.49	75	.....	...	.....	...	100
1893-94	8.59	91	.....	...	.....	...	.....	...	6.50	75	.....	...	7.80	79	4.95	57	.....	...	.....	...	75
1894-95	14.67	155	.....	...	.....	...	.....	...	10.69	123	.....	...	13.41	136	10.62	122	.....	...	.....	...	134
1895-96	8.20	86	.....	...	.....	...	.....	...	5.65	65	.....	...	7.39	75	6.43	74	.....	...	.....	...	75
1896-97	10.54	111	.....	...	.....	...	.....	...	10.65	123	.....	...	11.29	115	9.64	111	.....	...	.....	...	115
1897-98	4.96	52	5.91	46	.....	...	.....	...	5.26	61	.....	...	5.44	55	5.51	63	.....	...	.....	...	55
1898-99	7.84	83	8.23	64	.....	...	.....	...	7.96	92	.....	...	9.07	92	9.03	104	.....	...	.....	...	87
1899-00	10.28	108	13.39	103	.....	...	9.30	95	.....	...	8.74	103	9.83	100	9.83	113	7.77	106	13.89	96	103
1900-01	11.33	119	15.56	120	.....	...	13.68	139	.....	...	12.48	145	12.88	130	11.30	130	8.57	117	19.46	135	129
1901-02	6.87	72	7.76	60	.....	...	9.81	100	.....	...	6.73	78	8.83	90	6.94	80	5.02	68	11.04	76	78
1902-03	8.50	90	10.25	79	.....	...	8.36	85	.....	...	6.49	75	7.56	77	6.49	75	3.15	43	12.89	90	76
1903-04	8.04	85	.....	...	.....	...	8.32	85	.....	...	5.99	70	6.74	68	6.62	76	4.50	61	11.09	77	74
1904-05	12.08	127	.....	...	34.77	105	9.59	98	.....	...	10.47	122	11.49	117	13.42	154	7.22	98	19.71	137	120
1905-06	13.54	143	.....	...	51.65	156	13.69	139	.....	...	11.72	136	13.85	141	14.78	170	9.99	136	27.58	192	151
1906-07	10.84	114	16.57	128	38.01	115	10.21	104	.....	...	10.76	125	11.85	120	12.69	146	8.13	111	20.65	143	123
1907-08	7.72	81	7.53	58	22.97	69	8.24	84	11.10	128	8.47	98	10.01	102	9.49	109	6.76	92	13.29	92	86
1908-09	9.87	104	15.69	121	43.43	131	6.83	70	6.34	73	9.89	115	13.83	140	13.70	158	11.99	163	14.02	97	121
1909-10	10.99	116	13.09	101	34.58	104	9.66	98	9.61	111	7.61	88	8.87	90	8.94	103	7.01	95	13.22	92	95
1910-11	11.82	125	18.13	140	53.48	161	10.93	111	7.55	87	11.06	128	9.57	97	11.65	134	8.89	121	17.17	119	122
1911-12	7.34	77	9.43	73	23.60	71	6.18	63	6.78	78	6.39	74	5.10	52	6.71	77	3.49	48	12.11	84	70
1912-13	6.28	66	10.93	84	16.97	51	6.39	65	8.93	103	5.57	65	6.90	70	7.37	85	4.12	56	9.67	67	71
1913-14	11.04	116	17.64	136	48.54	146	8.47	86	11.01	127	10.58	123	9.54	97	8.84	102	7.20	98	15.27	106	114
1914-15	10.92	115	15.31	118	35.48	107	12.19	124	9.63	103	9.25	107	10.08	103	.....	...	11.68	159	16.57	115	117

Table 3--Records of precipitation at base-stations and indices of seasonal wetness--Concluded

Season	Fresno		Friant		North Fork		Madera		Kingsburg		Hanford		Visalia		Tulare		Angiola		Lemon Cove		Regional index of seasonal wetness
	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	Inches	Index	
1915-16	11.75	124	16.21	125	42.07	127	15.24	155	11.73	135	9.18	107	10.38	106	.....	...	7.93	108	16.73	116	122
1916-17	7.25	76	13.12	101	33.87	102	9.72	99	8.80	101	7.35	86	8.95	91	.....	...	5.06	69	12.51	87	92
1917-18	10.26	108	12.59	97	26.96	81	8.90	91	9.56	110	9.30	108	7.44	76	.....	...	6.16	84	9.20	64	91
1918-19	6.90	73	9.02	70	31.49	95	7.98	81	.....	...	6.29	73	8.35	85	.....	...	7.72	105	11.64	81	83
1919-20	8.24	87	10.36	80	31.30	94	5.88	60	.....	...	8.13	94	9.82	100	.....	...	6.46	88	14.18	98	88
1920-21	8.19	86	12.11	94	33.98	102	11.11	113	.....	...	7.83	91	9.14	93	.....	...	6.46	88	12.58	88	94
1921-22	10.83	114	15.68	121	37.76	114	14.42	147	.....	...	9.94	115	11.26	114	.....	...	8.84	120	16.45	114	120
1922-23	9.37	99	15.40	119	35.69	108	10.44	106	.....	...	8.23	96	9.72	99	.....	...	6.97	95	13.62	94	102
1923-24	5.24	55	8.06	62	14.99	45	5.49	56	.....	...	4.19	49	4.06	41	.....	...	4.79	65	6.24	43	52
1924-25	9.78	103	15.82	122	32.72	98	9.64	98	.....	...	8.56	100	10.38	106	.....	...	6.96	95	15.85	110	104
1925-26	9.37	99	10.66	82	26.02	78	6.34	65	.....	...	6.51	76	7.34	75	.....	...	5.50	75	9.73	68	77
1926-27	10.31	109	14.33	111	33.22	100	10.28	105	.....	...	11.21	130	11.06	112	.....	...	9.68	132	14.98	104	113
1927-28	6.75	71	12.65	98	25.74	77	9.21	94	.....	...	6.90	80	7.04	72	.....	...	6.66	90	9.21	64	81
1928-29	7.43	77	10.56	82	22.14	67	9.18	93	.....	...	7.03	82	7.57	77	.....	...	6.17	84	11.65	81	80
1929-30	6.42	68	11.16	86	19.66	59	6.07	62	.....	...	5.29	61	6.79	69	.....	...	4.94	67	9.98	69	68
1930-31	8.23	87	8.83	68	17.80	54	7.71	79	.....	...	6.78	79	6.67	68	.....	...	7.67	104	10.23	71	76
1931-32	9.58	102	14.73	114	37.61	113	9.22	94	.....	...	8.74	102	10.60	108	.....	...	8.65	118	17.02	118	109
1932-33	5.82	61	9.62	74	24.10	73	6.91	70	.....	...	5.97	69	8.13	83	.....	...	6.15	84	11.85	82	74
1933-34	4.43	47	6.86	53	19.06	57	5.75	59	.....	...	3.27	38	6.16	63	.....	...	4.11	56	7.32	51	53
1934-35	16.70	176	21.66	167	41.28	124	19.18	195	.....	...	13.37	155	15.64	159	.....	...	12.45	169	20.26	141	161
1935-36	10.48	110	15.60	21	36.65	110	12.70	129	.....	...	8.77	102	11.70	119	.....	...	8.19	111	17.86	124	116
1936-37	12.74	134	18.74	145	41.35	124	12.10	123	.....	...	11.57	134	13.79	140	.....	...	11.08	151	20.03	139	136
1937-38	15.85	167	21.00	162	60.59	182	17.29	176	.....	...	13.77	160	16.60	169	.....	...	12.36	168	21.54	150	167
1938-39	9.08	96	10.36	80	24.53	74	8.01	82	.....	...	6.69	78	8.18	83	.....	...	6.55	89	11.96	83	83
1939-40	11.50	121	16.87	130	41.28	124	12.13	124	.....	...	9.20	107	14.26	145	.....	...	8.49	116	19.88	138	126
Totals	569.01	...	517.45	...	1195.34	...	402.75	...	269.47	...	352.78	...	570.49	...	295.11	...	301.49	...	590.13	...	...
No. years	60	...	40	...	36	...	41	...	31	...	41	...	58	...	34	...	41	...	41	...	...
Averages	9.48	100	12.94	100	33.20	100	9.82	100	8.69	100	8.61	100	9.83	100	8.68	100	7.35	100	14.40	100	...

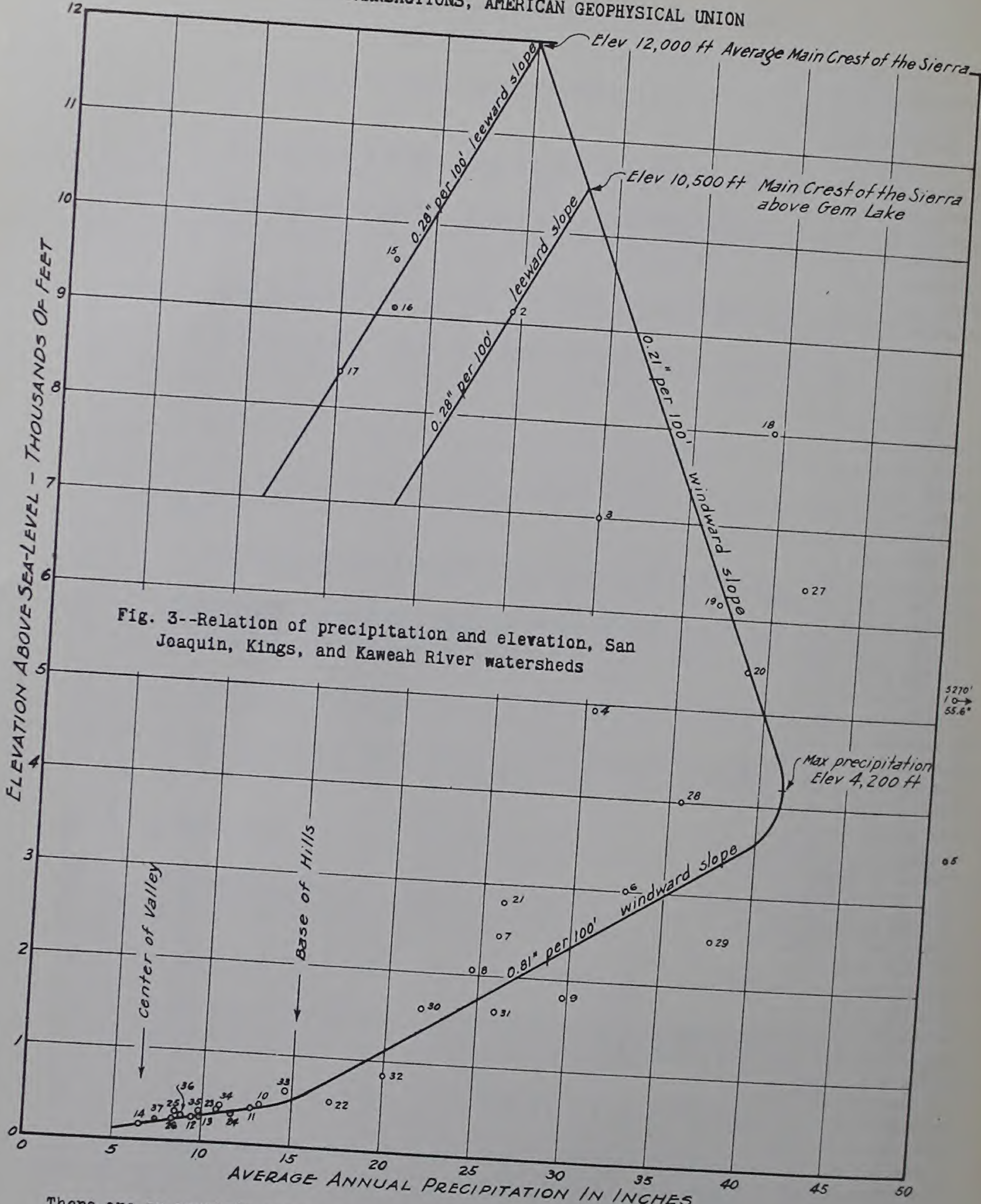

Fig. 3--Relation of precipitation and elevation, San Joaquin, Kings, and Kaweah River watersheds

There are no mountain ranges in California high enough to illustrate any portion of the second cycle of precipitation-increase and decrease which occur above 15,000 feet.

The differing rates of change of precipitation with elevation can be correlated with the degree of inclination of the mountain slopes up or down which the air-masses move when yielding precipitation.

Precipitation-elevation diagram for San Joaquin, Kings, Kaweah watersheds

There are at least 37 precipitation-stations within and near the watersheds of San Joaquin, Kings, and Kaweah rivers which have records of sufficient length for use in preparing a precipitation-elevation diagram. These records, as a composite, cover the 60-year period 1880 to 1940. They are listed and described on Table 2 and locations are shown on Figure 1. The records of the United States Weather Bureau are the source of the data. Elevations of these stations are well distributed and vary from 177 to 9120 feet above sea-level. The length of record at ten of

the stations exceeds 30 years and these have been selected as base-stations for computing indices of seasonal wetness (Table 3).

Study of the indices at the 37 stations indicates a general similarity in character each year throughout the whole area. A regional index can thus be computed annually applicable to all three watersheds. These indices were used to adjust short precipitation-records to the 60-year averages shown in the last column of Table 2. The latter quantities were the basis for preparing the precipitation-elevation graph shown on Figure 3. Although there is considerable scattering of supporting points on the diagram, there are definite trends for each distinct topographic slope and condition, and the general shape of the graph corresponds with that at the Central Pacific section which crosses the Sierra further north (Fig. 2). It is concluded that the graph represents with reasonable accuracy the conditions on the three selected watersheds.

Application to watersheds

The application of a precipitation-elevation diagram to a watershed for the purpose of delineating precipitation-contours (isohyelal lines) is greatly facilitated by a preliminary study of the topography and of the distribution of vegetation. From topographic maps the windward and leeward slopes can be identified, and also the precipitation-shadows and gaps, and the location of the contour of maximum precipitation. From forestry maps can be outlined the boundaries of the differing types of vegetation useful as indicators of precipitation-depth. This information if placed upon a detailed topographic map furnishes a general guide and check for the working out of precipitation-contours from precipitation-elevation diagrams. As an illustration, such data for the three selected watersheds have been included on Figure 1 and indicates the following for each of the areas.

The watershed of Kaweah River is open, with no transverse ridges to create leeward slopes. Dense uninterrupted forests of pine and fir cover the elevation-zone of 4000 to 8000 feet which includes the zone of maximum precipitation in the vicinity of elevation of 4200 feet. There are no apparent complications in the application of the precipitation-elevation diagram. Precipitation-contours were therefore laid out at five-inch intervals upon United States Geological Survey quadrangles (scale 1 inch to 2 inches) following the corresponding elevation-contours as indicated by the precipitation-elevation graph (Fig. 3). Average annual precipitation was found to vary from 17 inches at lowest elevation up to 41.3 inches at elevation of 4200 feet and down to 28 inches at the main crest. The average annual areal precipitation upon the watershed computed from areas between contours as measured by planimeter is 33.8 inches.

The watershed of Kings River extends to the main crest of the Sierra but with a barrier of high ridges cutting off the upper third of the Basin. Continuity of these ridges is broken by two major gaps represented by the canyons of the South and Middle forks. These gaps are of sufficient width to permit free atmospheric flow up-canyon during storms with consequent development of a fan-shaped area of heavy precipitation above the gaps. This condition is evidenced by the extension of the dense forest area of the middle watershed through both gaps. A minor gap further to the north is represented by the canyon of the North Fork. This gap is too narrow and at too high elevation for important air-flow and the area above has diminishing precipitation and lacks forest growth. Short cross ridges also form pockets at the heads of Helm Creek and Roaring River. These are open, however, and the projection of the densely forested area into them indicates free atmospheric flow during storms. The barriers, although forming local precipitation-shadows, are sufficiently broken to permit of free atmospheric flow and do not interfere with the normal application of the precipitation-elevation diagram. Precipitation-contours worked out as for the Kaweah indicate an average annual areal precipitation upon the watershed of 31.8 inches.

The San Joaquin Watershed is traversed midway by barrier ridges cut by a wide gap represented by the main river-canyon. There is a free atmospheric flow through this gap with a heavy precipitation-area fanning out to the east and extending up the Middle and South forks. This fact is evidenced by the extended projection of dense forest far up the watersheds of both forks. Precipitation-contours worked out as for the other watersheds show variations in annual precipitation of from 17 inches at the lowest elevation to 42 inches at maximum and 23 inches at the main crest. The average annual areal precipitation upon the watershed is 33.0 inches.

Precipitation-runoff differences

Runoff-records are available for the three selected watersheds for more than 40 years (Table 4). The annual runoff in acre-feet and as depth in inches has been compiled and entered upon Tables 5, 6, and 7. Average precipitation upon the watershed for each year has also been

Table 4--Description of stream-gaging station
(Data from records of United States Geological Survey)

Stream	Station	Area watershed, square miles	Period record	Length record, years	Average annual runoff	Storage
San Joaquin River	Hamptonville	1637	1880-1884	4		None
	Herndon	1637	1895-1901	6		None
	Friant	1632	1907-1940	33	1,740,000	Crane Valley Reservoir and Florence, Huntington, and Shaver lakes
Kings River	Slate Point	1742	1880-1884	4		None
	Piedra	1694	1895-1940	45	1,703,000	None
Kaweah River	Wachumna Hills	619	1880-1884	4		None
	Three Rivers	520	1903-1940	37	418,000	None

Table 5--Annual precipitation, runoff, and differences for San Joaquin River

Water-year, Sep 1 - June 30	Annual precip-itation, inches	Annual runoff in		Annual differ-ences, inches	Water-year, Sep 1 - June 30	Annual precip-itation, inches	Annual runoff in		Annual differ-ences, inches
		Acre-feet	Inches				Acre-feet	Inches	
1880-81	35.4	2,630,000	30.1	5.3	1910-11	40.3	3,560,000	40.7	0.4
1881-82	19.2	1,680,000	19.2	0.0	1911-12	23.1	1,041,000	11.9	11.2
1882-83	23.1	1,270,000	14.6	8.5	1912-13	23.4	868,000	10.0	13.4
1883-84	52.8	3,240,000	37.1	15.7	1913-14	37.7	2,865,000	32.9	4.8
1884-85	....	....	....	....	1914-15	38.6	1,960,000	22.5	16.1
1885-86	....	....	....	....	1915-16	40.3	2,760,000	31.7	8.6
1886-87	....	....	....	....	1916-17	30.4	1,940,000	22.3	8.1
1887-88	....	....	....	....	1917-18	30.0	1,461,000	16.8	13.2
1888-89	....	....	....	....	1918-19	27.4	1,317,000	15.1	12.3
1889-90	....	....	....	....	1919-20	29.1	1,303,000	15.0	14.1
1890-91	....	....	....	....	1920-21	31.0	1,592,000	18.3	12.7
1891-92	....	....	....	....	1921-22	39.7	2,325,000	26.7	13.0
1892-93	....	....	....	....	1922-23	33.4	1,664,000	19.1	14.3
1893-94	....	....	....	....	1923-24	17.2	505,000	5.8	11.4
1894-95	....	....	....	....	1924-25	34.4	1,360,000	15.6	18.8
1895-96	24.8	1,980,000	22.7	2.1	1925-26	25.4	1,165,000	13.4	12.0
1896-97	38.0	2,210,000	25.4	12.6	1926-27	37.3	1,947,000	22.4	14.9
1897-98	18.2	916,000	10.5	7.7	1927-28	26.7	1,160,000	13.3	13.4
1898-99	28.7	1,260,000	14.4	14.3	1928-29	26.4	880,000	10.1	16.3
1899-00	34.0	1,340,000	15.3	18.7	1929-30	22.4	869,000	10.0	12.4
1900-01	42.6	3,000,000	34.3	8.3	1930-31	25.1	563,000	6.5	18.6
1901-02	....	....	....	....	1931-32	36.0	1,850,000	21.2	14.8
1902-03	....	....	....	....	1932-33	24.4	1,150,000	13.2	11.2
1903-04	....	....	....	....	1933-34	17.5	819,000	9.4	8.1
1904-05	....	....	....	....	1934-35	53.2	1,776,000	20.4	32.8
1905-06	....	....	....	....	1935-36	38.3	1,855,000	21.3	17.0
1906-07	....	....	....	....	1936-37	45.0	2,227,000	25.6	19.4
1907-08	28.4	1,140,000	13.0	15.4	1937-38	55.1	3,592,000	41.2	13.9
1908-09	39.9	2,900,000	33.2	6.7	1938-39	27.4	1,077,000	12.4	15.0
1909-10	31.4	2,040,000	23.3	8.1	1939-40	41.6	1,829,000	21.0	20.6
Averages......................................						32.6	1,735,000	20.0	12.6

Table 6--Annual precipitation, runoff, and differences for Kings River

Water-year, Sep 1 - June 30	Annual precip-itation, inches	Annual runoff in		Annual differ-ences, inches	Water-year, Sep 1 - June 30	Annual precip-itation, inches	Annual runoff in		Annual differ-ences, inches
		Acre-feet	Inches				Acre-feet	Inches	
1880-81	34.0	1,870,000	20.1	13.9	1910-11	38.8	2,830,000	31.3	7.5
1881-82	18.5	1,510,000	16.3	2.2	1911-12	22.2	968,000	10.7	11.5
1882-83	22.3	1,280,000	13.8	8.5	1912-13	22.6	941,800	10.4	12.2
1883-84	50.9	3,380,000	36.4	14.5	1913-14	36.3	2,548,400	28.2	8.1
1884-85	....	....	....	....	1914-15	37.2	1,817,100	20.0	17.2
1885-86	....	....	....	....	1915-16	38.8	3,041,800	33.7	5.1
1886-87	....	....	....	....	1916-17	29.3	1,892,600	20.9	8.4
1887-88	....	....	....	....	1917-18	28.9	1,363,700	15.1	13.8
1888-89	....	....	....	....	1918-19	26.4	1,203,300	13.3	13.1
1889-90	....	....	....	....	1919-20	28.0	1,404,700	15.6	12.4
1890-91	....	....	....	....	1920-21	29.9	1,532,300	16.9	13.0
1891-92	....	....	....	....	1921-22	38.2	2,197,600	24.3	13.9
1892-93	....	....	....	....	1922-23	32.4	1,555,900	17.2	15.2
1893-94	....	....	....	....	1923-24	16.5	392,000	4.3	12.1
1894-95	....	....	....	....	1924-25	33.1	1,290,000	14.3	18.8
1895-96	23.8	1,850,000	20.5	3.3	1925-26	24.5	1,037,200	11.5	13.0
1896-97	36.6	2,090,000	23.1	13.5	1926-27	36.0	1,984,200	21.9	14.1
1897-98	17.5	881,000	9.8	7.7	1927-28	25.8	971,000	10.7	15.1
1898-99	28.0	1,220,000	13.5	14.5	1928-29	25.4	849,000	9.4	16.0
1899-00	32.8	1,290,000	14.3	18.5	1929-30	21.6	863,000	9.6	12.0
1900-01	41.0	3,140,000	34.8	6.2	1930-31	24.2	466,000	5.2	19.0
1901-02	24.8	1,550,000	17.2	7.6	1931-32	34.7	2,080,000	23.0	11.7
1902-03	24.2	1,690,000	18.7	5.5	1932-33	23.6	1,180,000	13.1	10.5
1903-04	23.6	1,740,000	19.3	4.3	1933-34	16.9	659,000	7.3	9.6
1904-05	38.2	1,430,000	15.8	22.4	1934-35	51.1	1,621,000	17.9	33.2
1905-06	48.0	3,260,000	36.1	11.9	1935-36	36.9	1,877,000	20.8	16.1
1906-07	39.1	2,750,000	30.4	8.7	1936-37	43.3	2,341,000	25.9	11.4
1907-08	27.4	1,030,000	11.4	16.0	1937-38	53.1	3,275,000	36.3	16.8
1908-09	38.5	2,810,000	31.1	7.4	1938-39	26.4	974,000	10.8	15.6
1909-10	30.2	1,780,000	19.7	10.5	1939-40	40.1	1,790,000	19.8	20.3
Averages..						31.4	1,703,000	18.8	12.6

entered on these Tables as computed by multiplying the regional index of seasonal wetness (Table 3) by the average annual precipitation upon the watershed as determined from the precipitation-elevation diagram. The annual differences appearing in the last column of the Tables are the computed difference of precipitation and runoff for each year. These quantities represent total evaporation from the watersheds plus or minus storage-differences at beginning and end of the year.

Examination of the Tables shows wide variation in the amount of the differences in all three of the watersheds, indicative of a large carry-over of snow from wet to dry years and an extensive building up of soil-moisture and snow in wet years following dry years. In recent years artificial storage on San Joaquin River has also affected the annual carry-over. The stream-flow records are of such length, however, that the effects of watershed-storage are entirely eliminated in the computed average annual differences. The latter therefore represent total evaporation and amount to 12.6 inches for both San Joaquin and Kings rivers, and 19.2 inches for Kaweah River (Tables 5, 6, and 7). Equality in the values for San Joaquin and Kings rivers is to be expected as the result of similarities in watershed. The greater total evaporation from the Kaweah Watershed is also to be expected, because of the greater percentage of dense forest cover and much smaller area of high barren watershed. The relatively low values for all three watersheds probably reflect the low air-temperatures which prevail over the high mountain areas.

Table 7--Annual precipitation, runoff, and differences for Kaweah River

Water-year, Sep 1 - June 30	Annual precip-itation, inches	Annual runoff in		Annual differ-ences, inches	Water-year, Sep 1 - June 30	Annual precip-itation, inches	Annual runoff in		Annual differ-ences, inches
		Acre-feet	Inches				Acre-feet	Inches	
1880-81	36.2	398,000	12.1	24.1	1910-11	41.2	546,000	19.7	21.5
1881-82	19.6	424,000	12.8	6.8	1911-12	23.7	207,400	7.5	16.2
1882-83	23.7	276,000	8.4	15.3	1912-13	24.0	220,700	8.0	16.0
1883-84	54.1	1,130,000	34.3	19.8	1913-14	38.5	486,000	17.5	21.0
1884-85	....	....	....	....	1914-15	39.6	369,500	13.3	26.3
1885-86	....	....	....	....	1915-16	41.2	762,200	27.4	13.8
1886-87	....	....	....	....	1916-17	31.1	471,500	17.0	14.1
1887-88	....	....	....	....	1917-18	30.8	229,700	8.3	22.5
1888-89	....	....	....	....	1918-19	28.0	289,200	10.4	17.6
1889-90	....	....	....	....	1919-20	29.8	372,100	13.4	16.4
1890-91	....	....	....	....	1920-21	31.8	360,800	13.0	18.8
1891-92	....	....	....	....	1921-22	40.5	461,100	16.6	23.9
1892-93	....	....	....	....	1922-23	34.5	363,500	13.1	21.4
1893-94	....	....	....	....	1923-24	17.6	101,700	3.6	14.0
1894-95	....	....	....	....	1924-25	35.2	325,500	11.7	23.5
1895-96	....	....	....	....	1925-26	26.0	218,800	7.8	18.2
1896-97	....	....	....	....	1926-27	38.2	483,200	17.4	20.8
1897-98	....	....	....	....	1927-28	27.4	203,000	7.3	20.1
1898-99	....	....	....	....	1928-29	27.0	223,000	8.0	19.0
1899-00	....	....	....	....	1929-30	21.9	218,000	7.8	14.1
1900-01	....	....	....	....	1930-31	25.7	114,000	4.1	21.6
1901-02	....	....	....	....	1931-32	37.0	520,000	18.7	18.3
1902-03	....	....	....	....	1932-33	24.6	284,000	10.2	14.4
1903-04	25.0	373,000	13.4	11.6	1933-34	17.9	131,000	4.7	13.2
1904-05	40.6	338,000	12.2	28.4	1934-35	54.4	357,600	12.8	41.6
1905-06	51.0	1,090,000	39.2	11.8	1935-36	39.2	486,900	17.5	21.7
1906-07	41.5	594,000	21.4	20.1	1936-37	46.0	677,200	24.4	21.6
1907-08	29.1	253,000	9.1	20.0	1937-38	56.5	870,900	31.4	25.1
1908-09	41.0	800,000	28.9	12.1	1938-39	28.1	247,200	8.9	19.2
1909-10	32.1	350,000	12.6	19.5	1939-40	42.5	510,000	18.4	24.1
Averages............						34.0	418,000	14.7	19.2

Runoff-curves

An effective method for analysis of differences of precipitation and runoff is the familiar precipitation-runoff diagram upon which quantities are plotted as inches depth over the watershed. The intercept between such a runoff-curve and the line of runoff of 100 per cent represents average total evaporation. To illustrate such an analysis the precipitation and runoff quantities on Tables 5, 6, and 7 have been plotted upon Figures 4, 5, and 6 and appropriate lines drawn to represent the average relation and also the ordinary limits. All these lines are found to be parallel to the lines of runoff of 100 per cent. The intercepts between the lines of average runoff of 100 per cent are 12.9 inches for San Joaquin River, 12.7 inches for Kings River, and 19.0 inches for Kaweah River. These correspond with the values of 12.6, 12.6, and 19.2 inches computed as the arithmetical averages on Tables 4, 5, and 6. The spread of plotted points between the limiting lines is 14 inches for San Joaquin and Kings rivers and 13.5 inches for Kaweah River. This spread represents the variation in precipitation-runoff differences due to watershed-storage and includes also any errors in computed precipitation upon the watershed or in measured stream-flow.

The few points beyond the limiting lines represent years in which precipitation differed greatly from that in the preceding year or years. The plotted point for the year 1881-82, for example, on all three diagrams lies close to the runoff-line of 100 per cent. This year was a very dry one and followed two wet years with large snow and soil-moisture carry-over. Similarly, the years 1904-05 and 1934-35 which lie to the right of the lower runoff-limit line were wet years following series of dry years during which snow-, lake-, and ground-storage were greatly

pleted. The years 1936-37 and 1939-40, which lie appreciably to the right for San Joaquin River only, probably reflect the effect upon that stream of surface-storage.

Considering streams in both humid and semi-arid regions there are three distinct types of runoff-curves (Fig. 7). The first type is illustrated by San Joaquin, Kings, and Kaweah rivers and also South Fork of the Yuba River. These watersheds are characterized by depth of annual precipitation in excess of total evaporation and occurring principally during the winter months when evaporation is the least. The runoff-curve for this condition is a straight line parallel to the runoff-line of 100 per cent, the vertical interval between the lines representing average annual total evaporation. This type is characteristic of mountainous watersheds of the Sierra Nevada and Cascade Mountains and of the Pacific Coast streams north of San Francisco.

A second type corresponds with the first except that its slope is flatter than the runoff-line of 100 per cent. It is representative of watersheds in which annual precipitation exceeds total evaporation but with considerable portion occurring during the summer months when evaporivity is greatest. Total evaporation varies appreciably from year to year for such streams and may differ from the average as much as 3.5 inches. The average total evaporation for a watershed can be obtained from the diagram, by entering the average precipitation. This type is characteristic of streams in the humid portion of the United States east of the 95th meridian as illustrated by the Merrimac, James, Chattahoochee, and Neosho rivers and also at higher levels in the Rocky Mountain and Great Basin regions.

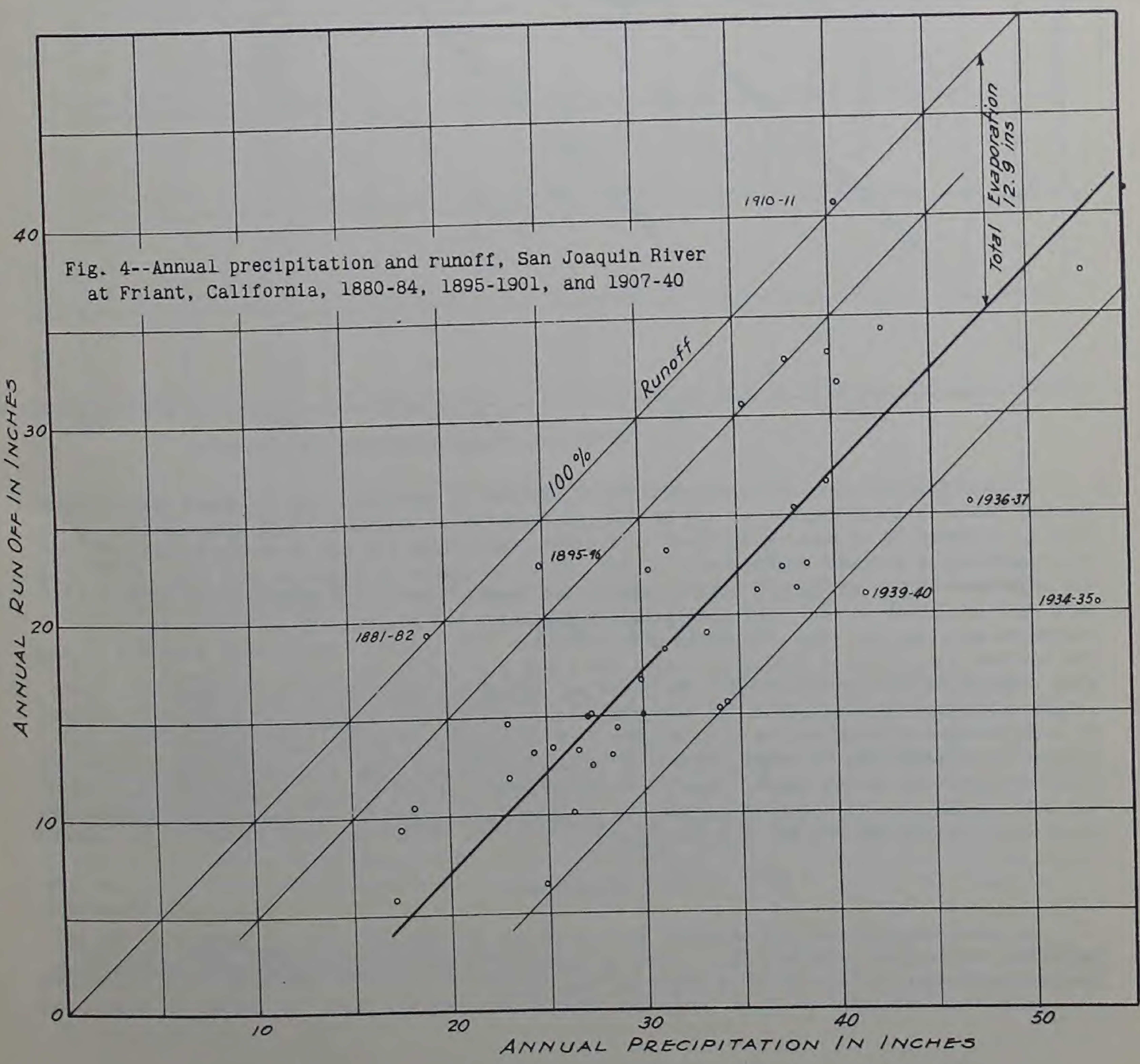

Fig. 4--Annual precipitation and runoff, San Joaquin River at Friant, California, 1880-84, 1895-1901, and 1907-40

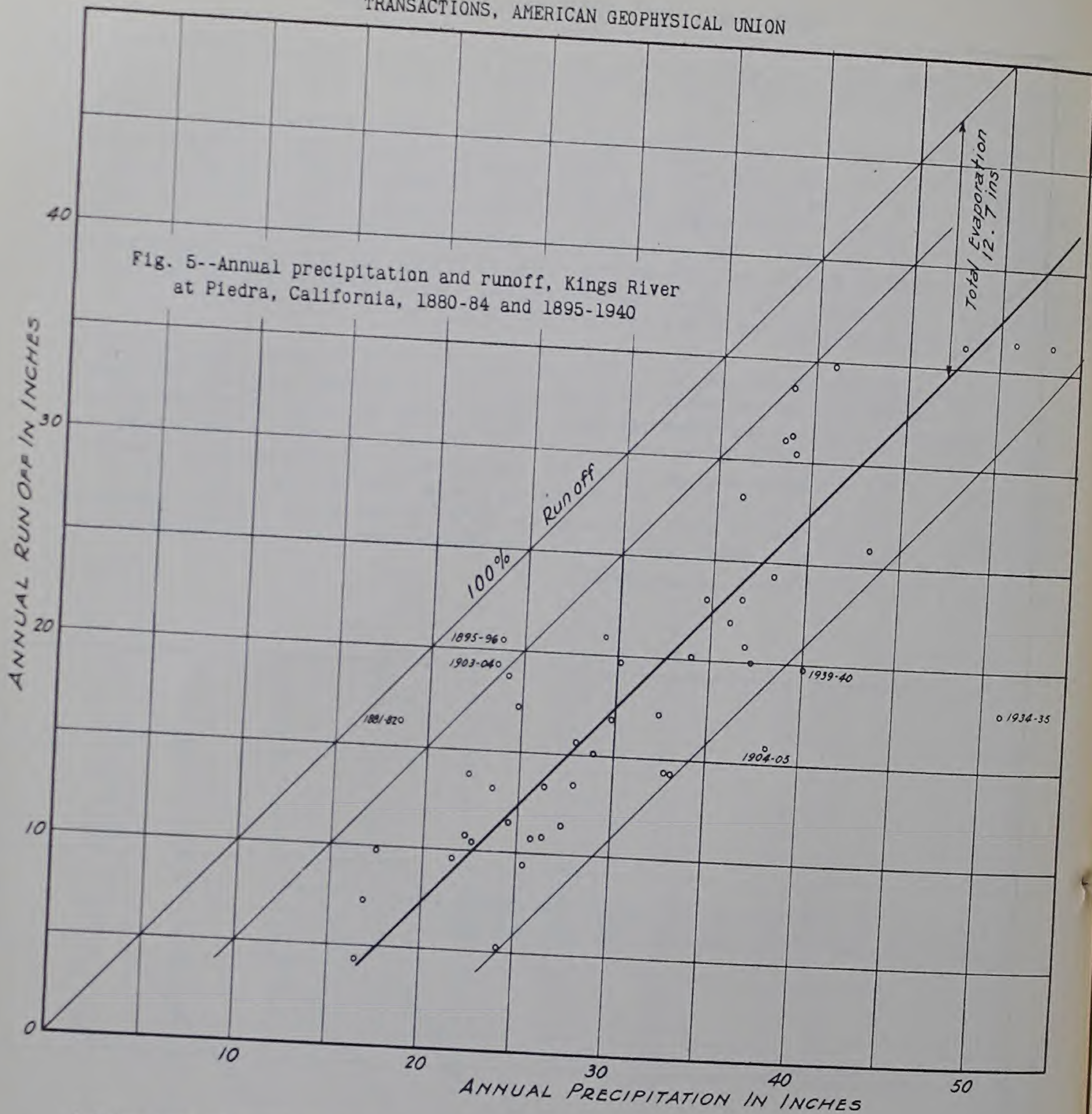

Fig. 5--Annual precipitation and runoff, Kings River at Piedra, California, 1880-84 and 1895-1940

A third type of curve is characteristic of streams in semi-arid regions where precipitation in many years is insufficient for the normal requirements of vegetation plus evaporation. This type is illustrated by Sweetwater River in Southern California and Red River in Minnesota. For this condition a minimum precipitation of from 10 to 15 inches is required each year for priming the watershed before any runoff occurs, except for unusual conditions such as high intensity or warm rain on frozen ground. For precipitation exceeding the minimum the percentage of runoff increases more rapidly than increasing precipitation. The typical runoff-curve commences at zero for minimum precipitation producing runoff and rises with sharp curvature. If the range in annual precipitation is great enough, the curve may ultimately approach or for a short distance follow a straight line of one of the two types described above. Vegetation on such watersheds is drought resistant and easily adjusts itself to variations in annual water-supply. Maximum transpiration occurring in years of greatest precipitation and total evaporation can be measured from the upper end of the curve. Runoff-curves of this type are typical of coastal streams on the Pacific Coast south of San Francisco, in Southern California, in the Great Basin, and in the Mississippi Valley west of the 95th meridian.

Conclusions

(1) Total evaporation from mountain watersheds can be computed if a topographic map of the watershed, sufficient precipitation-records to construct a precipitation-elevation diagram, and runoff-measurements for a series of years are available.

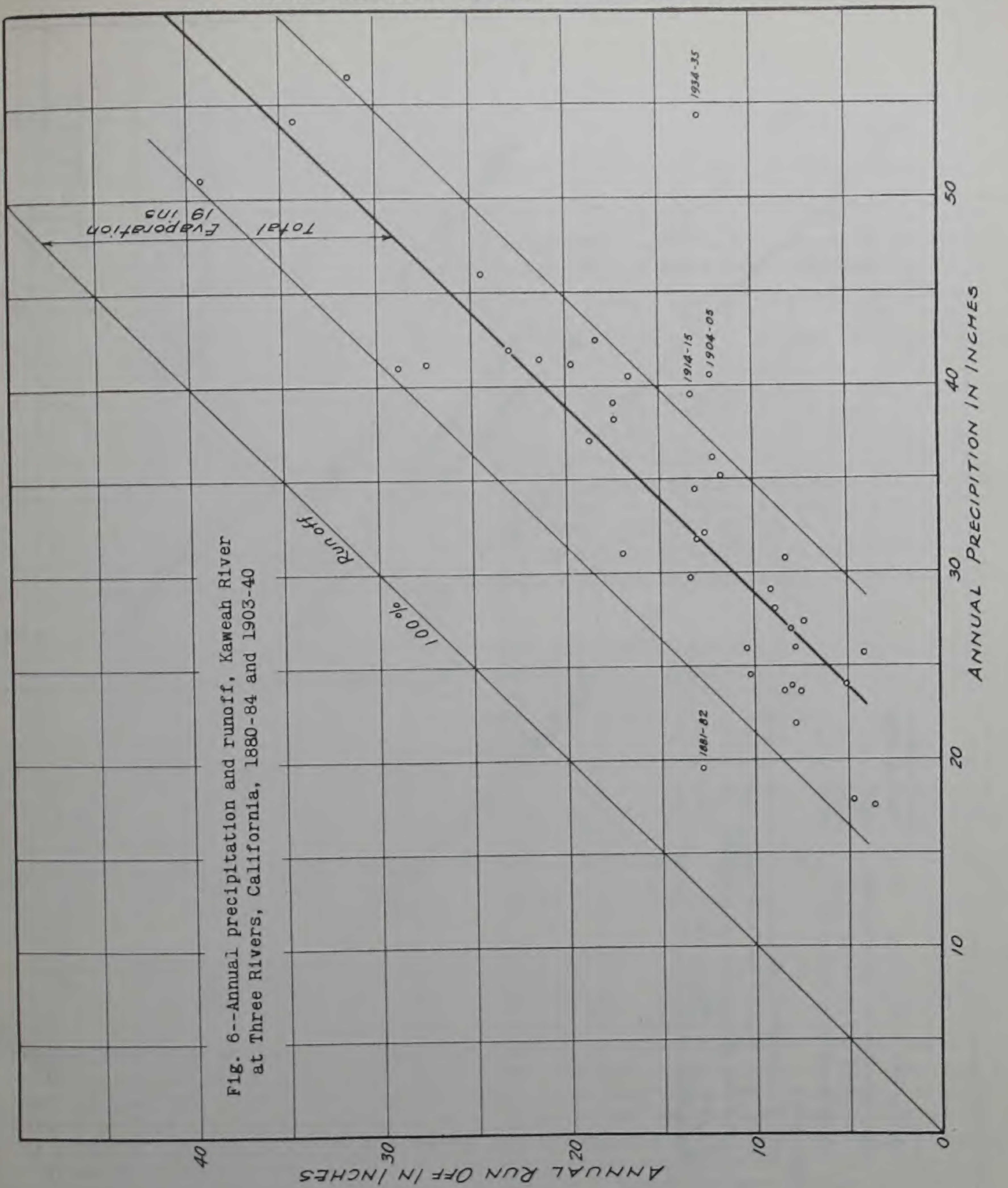

Fig. 6--Annual precipitation and runoff, Kaweah River at Three Rivers, California, 1880-84 and 1903-40

(2) The simplest and most effective method of analyzing precipitation- and runoff-data applying to a whole watershed is by reducing the runoff-quantities to inches of depth and plotting a precipitation-runoff diagram. The intercepts between such a runoff-curve and the line of runoff of 100 per cent represents total evaporation from the watershed for any given precipitation. If the relation is a straight line parallel to the line of runoff of 100 per cent, the annual total evaporation is constant. If inclined, the annual total evaporation varies, the average corresponding with the average precipitation. If the relation has curvature in the lower portion, the annual total evaporation varies, intercepts from the straight-line portion representing annual total evaporation for precipitation sufficiently large to supply all needs of growing vegetation.

(3) The annual total evaporation from watersheds lying on the western slope of the central and southern Sierra Nevada Mountains varies from 12.5 inches for high partially forested areas to at least 19 inches for areas having lower average elevation but more complete forestation.

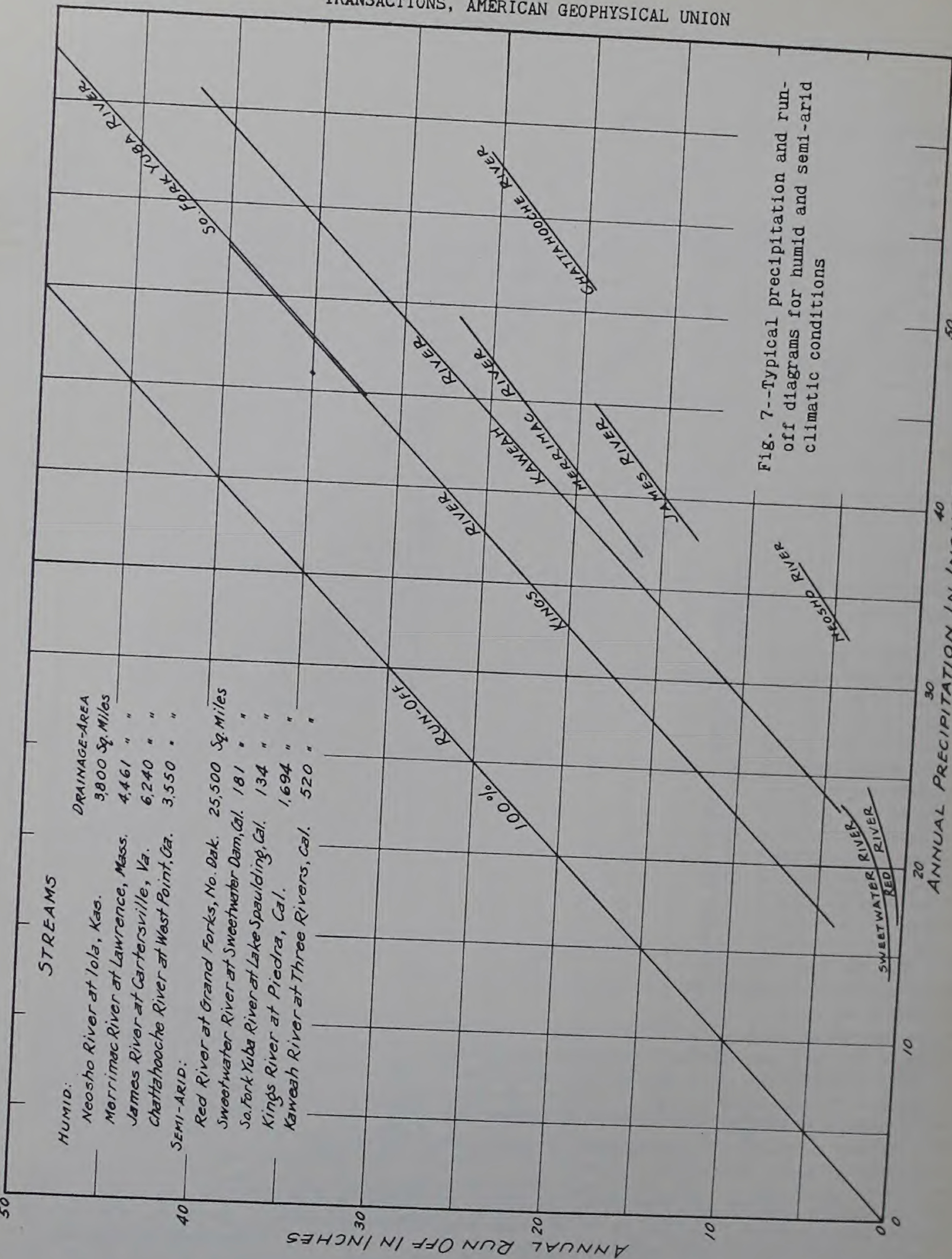

Fig. 7--Typical precipitation and run-off diagrams for humid and semi-arid climatic conditions

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DISCUSSION

ALFRED L. BROSIO (U. S. Engineers, Sacramento, California)--There are some questions in my mind regarding Mr. Lee's paper. Contrary to Mr. Lee's statements, it has been my impression that seasonal evaporation is more or less a function of seasonal precipitation, when the term evaporation is used as Mr. Lee used it, to include transpiration as well as "simple" evaporation.

Considering first the question of transpiration, it is certainly an undisputable fact that, within certain limits, vegetation transpires more water when there is more available for transpiration. Studies of tree-rings, as well as other scientific observations, have made this fact apparent. My own experience in gardening has taught me that, while plants will show normal growth when supplied with normal quantities of water, they will develop abnormally large areas of transpiration-surface when provided with excessive quantities of water. So much for the variation with seasonal precipitation.

Considering now the question of simple evaporation, it may be said that it is a function of temperature, atmospheric humidity, wind-velocity, and, certainly of great importance, the quantity of water which is brought within reach of the evaporation-factors. High temperature, low humidity, and high wind-velocity are not enough to effect simple evaporation; there must be water either on the ground-surface or close enough to the surface to be raised by capillary action to the surface. In a relatively wet season there is a greater quantity of such "available water" in the form of standing and moving surface-water during and following the more numerous storm-periods, in the form of more extensive area and longer duration of snow-cover, and in the form of additional ground-water.

Summarizing what I have said about transpiration and simple evaporation, it does seem that total evaporation should increase with seasonal precipitation. However, it is also true that seasonal precipitation, in our period of record, has never deviated far enough from the mean to clearly define, in a study such as Mr. Lee has made, any relation which may exist between total evaporation and precipitation. Certainly, the scatter of his plotted points, on his precipitation-runoff graph, is extensive enough so that his straight line, parallel to the runoff-line of 100 per cent and intersecting zero-runoff at a precipitation of about 12 inches, could reasonably be replaced by a curve the slope of which would increase from zero at the origin (indicating negligible runoff at relatively low values of seasonal precipitation) to a slope parallel to runoff of 100 per cent at some very high value of precipitation. Such a curve would imply an increase of total evaporation-losses with seasonal precipitation, very rapid at first, and reaching a theoretical maximum at infinity, although reaching a practical maximum within the range of historical events.

MR. LEE--That point is well taken and is illustrated in streams east of the 95th meridian where the characteristic rainfall occurs throughout the year. I was a little short in time at the end of my paper. On the last slide there was a group of streams east of the 95th meridian where the runoff-lines all had a slope which was not parallel to the runoff of 100 per cent. The more the rain the greater the evaporation. That condition is true in all of the area east of the 95th meridian. In these Sierra watersheds, on the other hand, the precipitation occurs in the winter-time. Experience shows that the evaporation during our winter rain-storms on the Pacific Coast is not very large compared to the total rainfall. It is relatively small and is more or less constant. Studies made in all our Pacific Coast watersheds, where there is sufficient precipitation to meet the evaporation-demands such as these streams discussed in this paper and streams in Oregon, all seem to show that the runoff-line is parallel to the line of 100 per cent which is a good indication of a fairly constant watershed-loss. That probably answers your question of more rain, more evaporation. In regard to the runoff with a 12-inch rainfall, it depends of course on the intensity of the storms and saturation of the ground. However, I know very definitely that in the Sweetwater Watershed in San Diego County, it takes about 11 inches to prime the Watershed. It varies probably two inches either way but the average is 11 inches to prime that Watershed. The runoff-lines for Kings and Kaweah, if projected, would, as you say, reach zero at about 12 inches of precipitation. For a rainfall and snowfall of an amount small enough to provide control for the line of relation down to the runoff-zero line, there would be some curvature concave upward toward the end. Those watersheds would probably show an 8-, 9-, or 10-inch precipitation necessary to prime the watershed before any runoff.

PHIL E. CHURCH (Assistant Professor of Geography and Meteorology, University of Washington, Seattle)--It seems to me that the hydrologists have two problems in this study in evaporation, namely, (1) the long-time evaporation during the course of the year in which it seems accepted to take the total amount of rainfall and subtract the runoff and (2) the balance attributable to

Table 1--Normal annual rainfall, Mokelumne Watershed, mountain area, 63-year period 1870-71 to 1933-34

Station	Elevation	Annual rainfall
	feet	inches
Lancha Plana	670	22.50
Electra	699[a]	31.50
Mokelumne Hill	1,400	29.71
Kennedy Mine	1,500	29.53
West Point	2,326	38.70
Tiger Creek	2,341[a]	45.80
Salt Springs	3,200[a]	42.90
Big Trees	4,700	51.10
Lake Alpine	7,500	48.00
Twin Lakes	7,920	42.20
Blue Lakes (Tamarack)	8,000	47.50

[a]In Mokelumne River Canyon and at substantially lower elevation than surrounding territory.

evaporation. For short periods you would not use that sort of procedure. I think we should investigate more thoroughly the new method for computing evaporation that was started by Dr. Sverdrup and has been developed still further by Dr. Rossby at Massachusetts Institute of Technology and Dr. Montgomery now at New York University.

THEODORE W. DANIEL (U. S. Forest Service, Berkeley, California)--Most rain-gages in the high mountains are situated at the bottoms of valleys. Would measurements of rainfall by these gages apply to areas of similar altitudes not situated in valleys? In other words, would you not expect significant differences in rainfall-measurements of gages situated on slopes and on ridge-tops in comparison with measurements of gages at similar altitudes in valleys? Further, would not these differences be accentuated at the higher altitudes where there is a greater range in elevations between the valley-floors and surrounding ridges?

MR. LEE--The mass as a whole is moving up a general slope and unless there are cross ridges the general movement controls and the gage would catch rain that originated far above in the upper levels but the rain would fall a considerable distance. The general movement of the air-mass as it goes up the slope is to fan out in the canyons and unless there is a barrier it continues across the slope.

L. STANDISH HALL (Hydraulic Engineer, East Bay Municipal Utility District, Oakland, California)--As I understand it, the speaker has drawn lines of equal precipitation following the contour-lines on the topographic map. It is questionable whether this method will give a true representation of the mean precipitation of the drainage-area. I have had occasion to study the precipitation on the Mokelumne River to a great extent and have noticed the small variation in mean annual precipitation between the canyon-rim and the river-stations. The records show that the rainfall in the canyons is only slightly less than that occurring at considerably higher elevations on the adjacent ridges. Table 1 gives the normal annual rainfall on the Mokelumne watershed for the mountain area, calculated for the 63-year mean from 1870-71 to 1933-34. From this Table it will be seen that at Electra the mean annual rainfall is 31.50 inches at an elevation of 699 feet. This station is immediately adjacent to Mokelumne Hill, which is at an elevation of 1,400 feet and the rainfall is only 29.71 inches. The mean elevation of the canyon-ridges surrounding Electra is approximately 2,000 feet. Further west in the foothills at the Lancha Plana Gage, located at Camp Pardee, the mean annual rainfall is only 22.50 inches, although the elevation is 670 feet, or practically the same level as at Electra. At Tiger Creek, an elevation of 2,341 feet, the rainfall is 45.80 inches. The elevation of the top of the canyon-rim adjacent to this station is approximately 3,500 feet. At West Point at elevation 2,326 feet, or very nearly the same level as at Tiger Creek, the mean precipitation is only 38.70 inches. At Salt Springs, elevation 3,200 feet, the mean annual precipitation is 42.90 inches. The elevation of the adjacent canyon-rim is approximately 6,500 feet. At Lake Alpine at elevation 7,500 feet, the mean annual precipitation is 48.00 inches.

"The variation in the rainfall and the runoff at certain stations may be a matter of rain-shadows." I wish Mr. Lee would explain what method he used to determine the extent of the rain-shadows. Some such condition must exist on the South and Middle forks of the Mokelumne River, as there is quite a difference in runoff expressed in inches of depth over the drainage-area for these two streams. Table 2 gives a comparison of the runoff in inches of depth with the mean elevation of Central Sierra drainages, including the Mokelumne River. It will be noted that for all the streams listed, with the exception of the Middle Fork of the Mokelumne River, there is a rather uniform relation between the mean elevation of the watershed and the runoff expressed in inches of depth. On the Middle Fork the runoff averages only 13.5-inch depths over the area, whereas a comparison of the elevation of the watershed and the runoff of the surrounding areas would indicate that the runoff should average 21.7 inches. The runoff, therefore, is only 62 per cent of what would normally be expected. There must be a very marked difference in precipitation between the Middle and South forks and also between the Middle Fork and the other surrounding drainage-areas. Unfortunately, there are no precipitation-stations in the drainage-areas of either the Middle or the South forks. The runoff from both tributaries should be approximately the same and the only factor that could make a difference is the location of Blue

Table 2--Comparison of runoff in inches depths with mean elevation of Central Sierra drainages

Stream	Drainage-area	Mean elevation	Runoff	Runoff-depth
	sq.mi.	feet	acre-feet	inches
Calaveras River	395	1930	248,000	11.8
Consumnes River	524	3047	401,000	14.4
North Fk. Consumnes River	198	3734	191,000	18.1
Middle Fk. Mokelumne River	68	4447	49,100	13.5
South Fk. Mokelumne River	37	4750	46,000	23.4
Mokelumne River	631	4868	825,000	24.5
Stanislaus River	935	5000±	1,275,000	25.6

Mountain. This high ridge, having a crest elevation of 6,070 feet, separates the central portion of the two drainage-areas. The wind-currents carrying precipitation generally come from the southwest, while the drainage-areas of both the Middle and South forks have their main axis lying in an almost due east-and-west direction. Blue Mountain and its adjacent ridges must cause a rain-shadow over a large part of the Middle Fork. I do not know whether Mr. Lee has tried to draw any conclusions as to the effect of differences in locations in drawing his lines of equal precipitation and in locating the rain-shadows.

MR. LEE--I do not attempt to make any segregation. I have no data over the forested area. It might be as great as 28 or 30 inches. I made no attempt to segregate. In regard to conditions on the South and Middle forks of the Mokelumne, I talked to Mr. Dolliver of the Division of Water Resources and I think there is a rainfall-shadow which causes the differences in runoff. There is a high cross-ridge that has to be taken into consideration. You can not apply a rainfall-diagram without taking into consideration ridges which present themselves to the storm and the movement of the air-mass. Each watershed has its own local peculiarities depending upon whether storm-movement is parallel or at right-angles to ridges. The cross-ridges on the Kings tend to give variation.

C. B. MEYER (Associate Hydraulic Engineer, State Division of Water Resources, Sacramento, California)--In the accompanying Table 1, precipitation-stations on the west slope of the southern Sierra Nevada Mountains are arranged according to their elevation above sea-level. The data shown in the Table were taken from the records of the Division of Water Resources of the State of California, which were obtained mainly from the United States Weather Bureau. Most of these stations are shown in Table 2 of Mr. Lee's paper. However, the mean annual precipitation shown in the accompanying Table 1 is based on a 50-year period in contrast to the 60-year mean shown in Mr. Lee's paper. The stations vary in elevation from 500 to 7,000 feet and the mean

Table 1--Precipitation-stations on west slope of southern Sierra Nevada Mountains arranged according to elevation

No.	Station	Watershed	Elevation	Period record	Average 50-year precipitation
			feet		inches
1	Huntington Lake	San Joaquin	7,000	1915-1940	30.43
2	General Grant Park	Kaweah	6,775	1924-1940	41.99
3	Giant Forest	Kaweah	6,360	1921-1940	42.23
4	Cliff Camp	Kings	6,150	1921-1940	39.88
5	Dinkey Meadow	Kings	5,440	1921-1935	40.18
6	Summerdale	Merced	5,000	1896-1912	54.64
7	Big Creek	San Joaquin	4,900	1915-1940	31.66
8	Springville	Tule	4,050	1907-1940	34.45
9	Crane Valley	San Joaquin	3,500	1903-1940	40.28
10	Hot Springs	Deer Creek	3,300	1907-1937	23.50
11	North Fork	San Joaquin	3,000	1904-1940	33.27
12	Auberry	San Joaquin	2,050	1915-1940	24.84
13	Mariposa	Mariposa Creek	2,000	1888-1940	32.75
14	Ash Mountain	Kaweah	1,600	1925-1940	26.12
15	Milo	Tule	1,600	1898-1922	22.31
16	Balch Camp	Kings	1,300	1926-1940	26.53
17	Three Rivers	Kaweah	840	1909-1940	19.77
18	Lemon Cove	Kaweah	600	1899-1940	14.80
19	Piedra	Kings	500	1917-1940	17.10

Table 2--Snow-survey courses on Kings, Kaweah, and San Joaquin River watersheds arranged according to elevation

Snow-survey course	Watershed	Elevation	Mean water-content, April 1
		feet	inches
Piute Pass	San Joaquin	11,200	35.8
Black Cap Pass	San Joaquin	10,800	42.4
Upper Burnt Corral Meadow	San Joaquin	9,700	40.1
Mammoth Pass	San Joaquin	9,500	48.5
Agnew Pass	San Joaquin	9,450	37.8
Kaiser Pass	San Joaquin	9,200	44.9
Swamp Meadow	Kings	9,000	46.0
Panther Meadow	Kaweah	8,650	39.9
Hockett Meadow	Kaweah	8,600	36.1
Helm Meadow	Kings	8,500	31.8
Long Meadow	Kings	8,500	34.2
Moraine Meadow	Kings	8,400	20.2
Statom Meadow	Kings	8,300	40.3
Post Corral Meadow	Kings	8,200	33.2
Sand Meadow	Kings	8,050	34.8
Quinn Ranger Station	Kaweah	8,000	24.1
Big Meadows	Kaweah	7,660	34.0
Horse Corral Meadow	Kings	7,600	23.8
Kennedy Meadow	Kings	7,600	23.3
Chilkoot Lake	San Joaquin	7,450	46.9
Bear Ridge	Kings	7,400	32.5
Chilkoot Meadow	San Joaquin	7,250	46.7
Florence Lake	San Joaquin	7,200	11.1
Fred Meadows	Kings	7,200	28.0
Huntington Lake	San Joaquin	7,000	28.2
General Grant Park	Kings	6,600	19.6
Giant Forest	Kaweah	6,360	21.9
Cliff Camp	Kings	6,300	18.6

annual precipitation varies from 14.80 inches to 54.64 inches. While the precipitation increases with the elevation, this is not the only factor causing variations in precipitation. Attention is called to the Big Creek and Summerdale stations with elevations of 4,900 and 5,000 feet and mean annual precipitations of 31.66 and 54.64 inches, respectively. The difference in elevation between these two stations cannot cause this great difference in precipitation. It is probable that the difference in the exposure of these stations to the rain-bearing winds is the major cause. Therefore, in order to develop a precipitation-elevation relationship as shown on Figure 3 of Mr. Lee's paper, it is necessary to have precipitation-records at a series of stations well distributed as to elevation and with nearly the same exposure to the rain-bearing winds. The data now available do not show such a series.

Table 2 accompanying this discussion shows snow-survey courses on the Kings, Kaweah, and San Joaquin River watersheds arranged according to elevation. The data shown in Table 2 were obtained from the reports of the California Cooperative Snow Survey of the Division of Water Resources. The mean water-content of the snow was based on measurements of the water-content of the snow on these courses over a period of ten years but the mean was extended to cover the 50-year period, 1889-1940, by obtaining the ratio of the April to July mean runoff of these streams for the period of snow-surveys to the April to July mean runoff for the 50-year period and applying this ratio to the mean water-content of the snow to obtain the mean water-content for the 50-year period. The courses vary in elevation from 6,300 to 11,200 feet and the mean water-content from 11.1 inches to 46.9 inches. The mean water-content of the snow on April 1 does not show the total annual precipitation and must always be less than the precipitation as usually some rain falls prior to the snow-season and some subsequent to April 1. However, for the courses at higher elevations, it is probable that the water-content on April 1 represents the major part of the season's precipitation. For courses at lower elevations, indications are that the water-content on April 1 represents only about half the seasonal precipitation. The maximum water-content in the snow appears to occur at elevations between 9,000 and 10,000 feet. The water-content at these courses exceeds the seasonal precipitation shown on the precipitation-elevation relation of Mr. Lee's Figure 3. Attention is called to the mean water-content for the

courses at Chilkoot Meadow and Florence Lake on the San Joaquin River. With only a difference in elevation of 50 feet, the water-content increases from 11.1 to 46.7 inches.

In conclusion, it would appear that with data now available it is not possible to construct an accurate precipitation-elevation diagram for the watersheds of the southern Sierra Nevada Mountains. Also, it would appear that the zone of maximum precipitation is not at an elevation as low as 4,200 feet as shown on Figure 3. Any inaccuracy in the precipitation-elevation diagram would be reflected in the evaporation as it was obtained from the differences between the precipitation and runoff.

CHARLES H. LEE on discussion by C. B. MEYER (communication of January 29, 1941)--(1) Differences in exposures are unquestionably the cause of some of the irregularity in precipitation at various stations both as measured by the United States Weather Bureau and at the snow-survey courses. It must be recognized that watershed-exposures are also different at various points, so that selection of stations for developing a precipitation-elevation diagram, all of which had the same exposure to rain-bearing winds, would not produce a diagram applicable to the watershed. The best that can be done is to strike an average using all available stations and having in mind the general form which such a curve should take. Such a curve as I have drawn is believed to be more representative of the watershed as a whole.

(2) Adjustment of ten-year snow-record and 50-year period is best made by using indices of seasonal wetness rather than runoff, in my opinion. For example, the precipitation for the ten-year period 1930-1940 is 10.1 per cent above the 60-year average (Table 3) while San Joaquin River runoff is 3.5 per cent below (Table 5), Kings River five per cent below (Table 6), and Kaweah River 0.4 per cent above. Snow on the ground as measured does not necessarily appear as runoff the same year. It may not all melt or may be held in ground- or lake-storage and appear in a succeeding year or be consumed before reaching the stream. If indices of seasonal wetness were used for correction, your mean water-content values on April 1 might be 15 per cent or more or less than those shown on Mr. Meyer's Table 2.

(3) Plotting values for stations above 7,000 feet from Mr. Meyer's Table 2 on my Figure 3 shows that of 11 points in Kings River five fall near my curve, two fall to the right, and four fall to the left. In other words, the preponderant value does not indicate precipitation greater than that shown by my curve. For Kaweah River two points fall near and one to the right of my curve. For San Joaquin River all nine points fall to the right of my curve. This has a preponderance indicating larger precipitation but with a correction with 15 per cent or more reduction these points would fall very much closer to the curve.

(4) Using the record of 1903-1940 at Crane Valley which Mr. Meyer gives in his Table 1 instead of the value of 1903-1921 that I used, the point falls practically on my curve (Fig. 3) instead of to the right.

(5) It is possible that more complete data would raise the elevation of maximum average rainfall somewhat above 4,200 feet but it is not believed that it would be much if any above 5,000 feet. Also, it is possible that the upper arm of my windward curve should be shifted a little to the right. If this were done the correction in computed evaporation would be much less than the correction for precipitation, as the latter would apply only to a portion of the watershed. It is also possible that precipitation on the San Joaquin River is greater than Kings River and that a separate elevation-precipitation diagram should be developed for it.

I appreciate Mr. Meyer's participation in the discussion and especially the opportunity to review the snow-catch data.

A 100-YEAR RECORD OF TRUCKEE RIVER RUNOFF ESTIMATED FROM CHANGES IN LEVELS AND VOLUMES OF PYRAMID AND WINNEMUCCA LAKES

George Hardman and Cruz Venstrom

Introduction

Pyramid Lake, in Washoe County, Nevada, is celebrated as a scenic attraction and for generations before the coming of the white man it supplied enormous quantities of fish to the original inhabitants. Indians, from as far distant as Lovelock, gathered on the banks of the Truckee River at the beginning of the first-high water in the spring, when countless numbers of Pyramid Lake trout and other fish ascended the River to their spawning grounds.

After the coming of the white man, tons of fine fish were sent yearly to markets in California and Nevada. From all over America sportsmen journeyed to the Lake, and the Pyramid Lake trout, largest known of the species, became famous as a game-fish. Today, the Lake stands 50 feet below its former normal level. The Truckee River enters now through a wide sandy mouth over which few fish can ascend, and very few are now caught in the Lake by sportsmen. However, to the thousands of people who annually visit its shores, Pyramid Lake presents a scene of majestic beauty.

The use of water for irrigation in Nevada has developed to the point where only in the wetter years is much water unused. Severe downward fluctuations in the supply, either annual or periodic, are usually attended by distressed conditions on the farms. Long records of stream-runoff, therefore, are not only interesting, but are valuable in describing the climatic environment to which the people must adapt their farming in order to achieve agricultural stability. Attention was first directed to Pyramid and Winnemucca lakes as a possible source of a long runoff-record because they receive and evaporate the flow of Truckee River; the levels of the lakes rise and fall with variations in the flow of the Truckee River, and these changes in elevation have been recorded frequently and accurately since the discovery of Pyramid Lake by Captain Fremont in 1844.

The subject of the annual flow of Truckee River has received considerable attention in recent years, and efforts have been made to correlate river-discharge with changes in the levels of Pyramid and Winnemucca lakes. The present study, which is based on the data presented below on the changes in the levels of Pyramid and Winnemucca lakes, is somewhat more detailed than those which have been brought to the attention of the writers.

Taylor [see 1 of "references" at end of paper] in 1901 and 1902 made a rather detailed study of the water-supply and precipitation-conditions of the Truckee River Basin. He made an attempt to correlate the river-discharge with the volume of water evaporated from the lakes, but did not develop the idea.

Antevs [2] in his book "Rainfall and tree growth in the Great Basin" gives a comprehensive review of weather conditions in this area since about 1850. In developing the curves of the volumes of water in Pyramid and Winnemucca lakes, Antevs apparently madeno attempt to account for the comparatively large quantities of water used within the Basin and diverted to points outside it.

In 1935, S. T. Harding reported a study of changes in levels of several Great Basin lakes [3]. Included in the study were Great Salt Lake, Pyramid Lake, Lake Tahoe, Eagle Lake, Mono Lake, and Walker Lake. Mono Lake has been little affected by changes in natural conditions, and Eagle Lake was little changed prior to 1924 when the Lake was tapped by a tunnel. Both these lakes show a long period of rising water which apparently began about 1860 and continued to about 1918. In contrast to the behavior of Eagle and Mono lakes, the record of Pyramid Lake indicates that it reached its highest level about 1871. Harding, in discussing the changes in the levels of Pyramid Lake, states that "general computations of consumptive use indicate that without irrigation-diversion, Pyramid Lake would have been higher in 1917 than it was in 1890, with overflow to Winnemucca Lake, and would not now (1935) be as low as it was in 1844."

A study of the growth of western yellow-pine trees on the Truckee River Watershed as a measure of precipitation- and runoff-conditions was made by the senior author in 1934 and 1935 [4]. The smoothed curves of average ring-widths indicate a period of moisture-deficiency for many years prior to about 1860 or 1870. This period was followed by generally favorable growing conditions which lasted until about 1915. Tree-growth has been greatly depressed during the past 20 years.

The present study brings together all the available evidence, both direct and indirect, of the changes which have taken place in the levels of these two lakes and in the volumes of water contained in them since 1840, and presents estimates of what these changes would have been under undisturbed natural conditions. From these estimates a record of the seasonal flow of the Truckee River for the past 100 years has been developed.

Description

Pyramid Lake, discovered by Captain John C. Fremont [5] in January, 1844, lies about 40 miles northeast of Reno, Nevada. Winnemucca Lake, now reduced to a mud-flat, lies about five to six miles east of Pyramid Lake and for most of its length is separated from it by the high, narrow Lake Range. Pyramid Lake is about 30 miles long and from 8 to 12 miles wide, while Winne-

mucca Lake at its highest level was about 25 miles long and averaged about 3-1/2 miles wide. Pyramid Lake in 1882, when it stood about at the level of overflow to Winnemucca Lake, was about 360 feet deep and Winnemucca Lake was about 85 feet deep. The water of Pyramid Lake contained about 3,500 parts per million of total solids when analyzed in 1882. The water of Winnemucca Lake in 1882 was very similar to that of Pyramid Lake and only slightly more concentrated.

Both lakes receive the major portion of their water-supply from the Truckee River which heads in Lake Tahoe and drains the surrounding area in the Sierra Nevada Mountains. A narrow channel, known as Mud Lake Slough or Winnemucca Slough, heads on the Truckee River near its point of discharge into Pyramid Lake, and leads to Winnemucca Lake. This slough has a length of about 4-1/2 miles, a fall of about eight feet, and a capacity of about 1,000 second-feet. A narrow flood-plain borders the slough-channel. The elevation of the slough where it leaves Truckee River is about 3,863 feet and that of the ground-surface in the region of bifurcation is about 3,872 feet.

Captain Fremont [5] mentioned the presence of a white line on the shores of Pyramid Lake, which he called the spring high-water mark, about 10 to 12 feet above the water-level in 1844. This white line is at an elevation of about 3,872 to 3,873 feet as determined by instrument leveling, and is about eight to nine feet above the level of the botton of Winnemucca Slough. The line is composed of a calcium-carbonate coating on the shore-rocks and its deposition may have been associated with the action of blue-green algae. This process has been fully described by Jones in his discussion of the tufa formations of Lake Lahontan [8].

Some few feet below the top of the white line, and a few feet above the level of the channel leading to Winnemucca Lake, is a well-defined terrace. The white line and associated terrace form one of the most prominent physical features of the shore of the Lake in the present low-water stage. The terrace is particularly well developed on Pyramid Island, but with the Lake filled well above the overflow-level, the terrace would not be so noticeable as at the present low level of the Lake.

When the relations existing between the elevation and capacity of Winnemucca Slough and flood-plain, and the elevation of the white line and associated terrace on the shores of Pyramid Lake are considered, certain deductions regarding the probable usual levels of Pyramid Lake seem reasonable.

It would seem that Pyramid Lake would periodically rise to the white line following the spring runoff of the Truckee River. At this level considerable overflow through Winnemucca Slough would occur, which, together with the usual loss of water by evaporation, would tend to reduce the Lake by late summer to about the level of Winnemucca Slough. In winter the flow of Truckee River would tend to balance the losses from evaporation and flow through Winnemucca Slough, and to maintain Pyramid Lake at a fairly constant level.

Great flood years, such as those of 1862, 1868, 1876, and 1890, or continued stormy periods, would contribute quantities of water which were very large in comparison to the surface-area of Pyramid Lake, and would result in rapid rises in the level of the Lake. Since the capacity of Winnemucca Slough is quite limited, the level of Pyramid Lake would rise to a point considerably above the level of the Slough following such periods of high precipitation. However, with an open channel to draw off the surplus water, such high levels of Pyramid Lake would necessarily have been very temporary. If Truckee River, during an abnormally dry period, could not supply sufficient water to balance evaporation from Pyramid Lake at a normal level, the Lake would fall until the increment from the River balanced evaporation from the decreased surface-area.

Lake-levels

Elevations of Pyramid Lake and its surroundings have been recorded on the base-datum in use at the time the observations were made. In this study all data have been correlated to the United States Coast and Geodetic Survey datum-line of 1931.

While Fremont in 1844 had no means of accurately determining the elevation of the surface of the Lake, the details of certain shore-features were sketched with such clarity that identification is possible. From these details it has been determined that the water-level in 1844 was about 3,860 feet on the datum of the United States Coast and Geodetic Survey. This is about three feet below the level of Winnemucca Slough, but the Lake was visited in January when near its lowest point for the year.

Fremont makes no mention of any other lake in this vicinity, although he was particularly

concerned with major drainage-features and camped close by an Indian Village near the present site of the town of Nixon. If another lake of any considerable size had been located within a few miles it seems obvious that the Indians would have conveyed the information to Fremont, who would have mentioned the fact in his report and drawn the lake on his map. Also on his map Winnemucca Slough is shown as rising in the hills to the east and flowing into Pyramid Lake. From this it might be inferred that there was no current, or more probably no water, in the Slough. The omission of any mention of a second lake and the fact that the level of Pyramid Lake was below the mouth of Winnemucca Slough leads to the conclusion that Winnemucca Lake was dry or very low at that time.

In addition to the negative evidence contained in the omission of any mention of Winnemucca Lake by Fremont, several early maps of this area present considerable evidence indicating that this Lake was dry or nearly so. On the Overland Road Guide map [9] published about 1850, the outlines of Pyramid Lake are shown much as they are today, but Winnemucca Lake appears as a very small pond in the north-central part of the Basin. In 1854 Lieutenant Beckwith [10] explored the Black Rock Desert Area in search of a route for a railroad to the west coast. A sketch-map of the surrounding area was made from a high point in the north end of the Lake Range which commanded a broad view of the adjacent territory. To the northeast of Pyramid Lake is shown a small playa lake similar to those farther north in the Black Rock Desert. This playa may be Winnemucca Lake.

A map of California and part of the Nevada Territory prepared by the General Land Office [6] for its report for the year 1865, covers this area. The map shows Pyramid Lake and surrounding territory quite accurately. Winnemucca Lake is indicated as a very small body of water.

Another mention of Winnemucca Lake is made in the accounts of the Indian fights of 1860, as reported by S. S. Buckland [11]. During this excitement a small expedition chased a band of Indians along the west shore of Winnemucca Lake, which was then called Mud Lake. An editorial note states that the Lake was then 10 or 12 miles long.

R. H. Cowles, who has operated a ranch on Winnemucca Slough near its mouth since prior to 1880, in a conversation with the writers stated that the Pyramid Lake Indians report that Winnemucca Lake was dry for some time prior to the coming of the white man. From their statements there was a slight filling of the Lake, a recession, and then a continued rise which culminated in a full lake.

There are no records of the elevations of Pyramid or Winnemucca lakes from 1844 to 1867. Weather records for the San Francisco-Sacramento Valley area indicate several years of moderate to low precipitation after 1850 and Pyramid Lake probably remained at a low level.

The year 1859-60 seems to have been one of above average precipitation with wide-spread floods throughout Nevada and California. One of the greatest floods in the history of Nevada occurred in 1861-62. It is estimated that Pyramid Lake rose to about a normal level of 3,865 feet in 1860 and to the exceptionally high level of 3,879 feet in 1862.

C. L. King [7] visited the area in 1867. He reported that Winnemucca Lake was then about 80 feet lower than Pyramid Lake. The presence of dead trees some distance from the shore in both Winnemucca and Pyramid indicated that the lakes were rising. Russell [12] reported the observations of George Frazier who had been familiar with the area since 1862. Frazier reported that before 1862 Winnemucca Lake was confined to a small area in the north end of the Basin, being joined to Winnemucca Slough by a channel which ran across about 15 miles of bottom land. King states that in 1867 this channel across the bottom of Winnemucca Lake could still be traced by the line of dead trees. Tree stumps along this channel have been observed by E. P. Osgood and S. T. Harding since the desiccation of the Lake in recent years.

In 1871 King again visited the area, finding that Pyramid Lake had risen about nine feet and Winnemucca Lake about 22 feet, the difference in the level of the two lakes now being 67 feet. The extremely high level of Pyramid Lake was probably due to the extraordinarily high runoff of the period from 1866 to 1869. From reports, the flood of 1867-68 is thought to rank with the flood of 1861-62 as one of the two greatest known flows on Truckee River. King observed that after 1867 Pyramid Lake rose until it overflowed the head of Winnemucca Slough. A photograph of Pyramid Island, by T. H. O'Sullivan, photographer for the 40th Parallel Survey, shows the water in Pyramid Lake at an elevation of about 3,876 feet. It has been assumed by other students of the problem that this photograph dates from King's first visit to the Lake in 1867 and has been used in connection with his statement of a nine-foot rise between 1867 and 1871 to establish an elevation of 3,885 feet in the latter year. [The United States War Department, under whose

FIG. 1--PYRAMID ISLAND AND TUFA-DOMES

Fig. 1-A--From the first known photograph of Pyramid Lake assumed to have been taken about 1871 by T. H. O'Sullivan for Clarence King on 40th Parallel Survey and shows water-level about 3,876 feet, U. S. Coast and Geodetic Survey datum; compare with B and C

Fig. 1-B--From photograph in 1882 by I. C. Russell in "Geological history of Lake Lahotan"; elevation of Lake about 3,865 to 3,867 feet, U. S. Coast and Geodetic Survey datum

Fig. 1-C--From photograph in 1939 by George Hardman and Cruz Venstrom taken from identical spot of King's photograph; water-level in Lake about 3,817 feet, U. S. Coast and Geodetic Survey datum

jurisdiction the Fortieth Parallel Survey was made, was unable to locate the records of the picture (Fig. 1-A).]

Russell states that recent tufa-deposits and lines of bleached algae about 12 feet above the water-level in 1882 gave evidence of a recent high level. These markings, which show very plainly in Russell's photographs of the tufa-domes at Pyramid Island, are still clearly visible in sheltered places and can be detected in recent photographs. The highest marks were found by instrument-leveling by the writers and others to be at an elevation of 3,879 feet, or just 12 feet above the water-level of 3,867 feet in 1882 (Fig. 1-B). [The lake in the vicinity of Pyramid Island was studied by the writers in September, 1939. On December 19, 1939, it was visited by a group consisting of V. P. Gianella, geologist of the University of Nevada School of Mines, and W. D. Bray, R. S. LaMotte, Harold E. Russell of the United States Army Engineers, and the writers.] There is no evidence in the photographs of a water-mark higher than about 12 feet above the water-level in 1882. Also, it is significant that Russell makes no mention of a water-mark that could be correlated with a higher elevation. Russell's observations were made not more than 15 years after the high elevation recorded by King was assumed to have been reached, and it is only reasonable to expect that very definite evidence of such a recent high level would have been present and very plain to such an experienced observer. From the records and photographs of Russell and from recent observations of water-marks, beach-lines, and shore vegetation, it is the opinion of the writers that the highest recent elevation of Pyramid Lake was not greater than 3,879 feet.

In line with this reasoning, the date of King's photograph of Pyramid Island is accepted as 1871 and the corresponding elevation of the Lake is fixed at 3,876 feet; then, in accordance with King's statement that Pyramid Lake rose nine feet between 1867 and 1871, the elevation of the Lake in 1867 becomes about 3,867 feet. This agrees with King's statement that at the time of his first visit in 1867 the River bifurcated and that later backwater covered the area of bifurcation. With the Lake at a normal level, the flood-flows of the Truckee River tend naturally to divide, but when Pyramid Lake stood at an elevation of 3,876 feet the area of bifurcation

would be flooded from Truckee River to the foot of the Marble Bluff to a depth of from one to five feet. The accompanying sketch-map of Figure 2 of a small segment of the Valley in the region of bifurcation, taken from a detailed topographic survey made in 1938 indicates the area that would be flooded by Pyramid Lake at an elevation of about 3,876 feet [13]. Small details from the Fortieth Parallel and Russell surveys, which show the shore of the Lake and the region of bifurcation according to the surveys of 1867 [14] and 1882, are also shown on this sketch.

The water-year of 1867-68 was characterized by extremely high floods and it seems entirely probable that the runoff was correspondingly heavy. Russell, reporting the observations of George Frazier, states that Pyramid Lake rose 10 to 15 feet in 1868 and continued to rise the following year. From the rather scant indications, it is assumed that Pyramid Lake rose to an elevation of about 3,879 feet in 1868 or 1869, and was reduced from this high level by overflow to Winnemucca Lake and by evaporation during the relatively dry years of 1869-70 and 1870-71 to the elevation of 3,876 feet as estimated from King's records and photographs.

In considering the relative elevations of Winnemucca Lake, it seems possible that errors may have been made in the original levels from which the differences in elevations between Pyramid

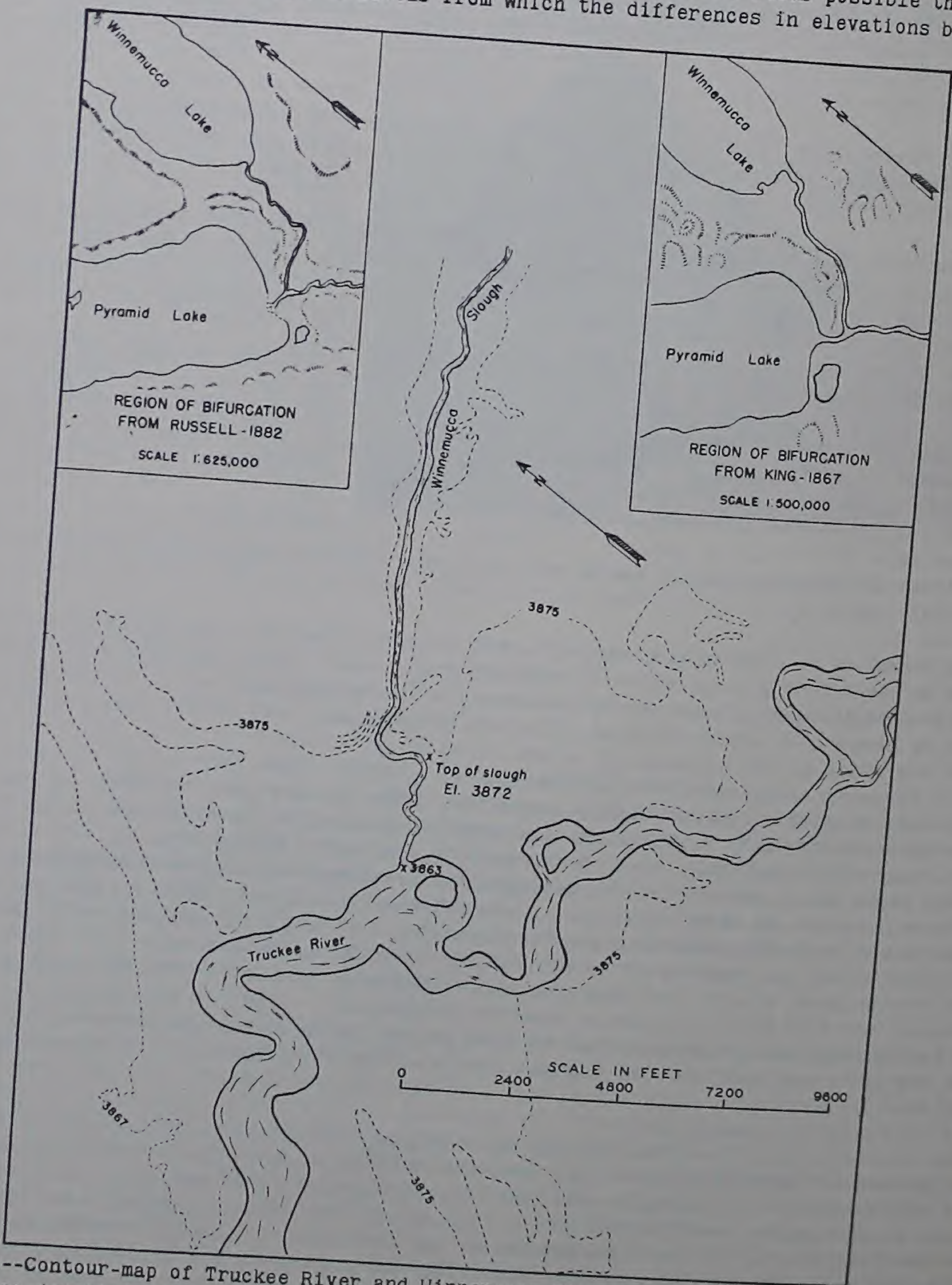

Fig. 2--Contour-map of Truckee River and Winnemucca Slough in region of bifurcation (From detailed contour-map of 1938 prepared by Nevada Agricultural Experiment Station, Department of Irrigation, as also Figures 3, 4, and 5)

and Winnemucca lakes, of 80 feet in 1867 and 67 feet in 1871, have been estimated. The levels were probably determined from barometric readings, and typographical errors may have occurred in printing. Several typographical errors have been noted in printed data of this period.

From records of the floods of 1861-62 and 1867-68 it appears that extraordinarily large quantities of water passed down the Truckee River, and Winnemucca Lake could have risen faster than the written records indicate. George Frazier's statements, as reported by Russell, that the meadows which existed on the south end of the bottom of Winnemucca Lake prior to 1862 were covered by 15 to 20 feet of water after 1862, gives a hint of the actual depth of the Lake. The water at this end of the Lake would be from 20 to 40 feet shallower than at the center and north end of the Lake.

King [7] states that the outlines of the two lakes given in the topographic map of the Fortieth Parallel Survey are according to the survey of 1867 and, in his words, "form interesting data for future comparisons." A check of the area of Winnemucca Lake, as shown on this map, indicates an area of about 78 to 80 square miles, which corresponds to a depth of about 55 to 60 feet and a volume of about 1,800,000 acre-feet. This depth checks fairly well with reports of observations by King and others, and correlates well with observations on the quantities of water entering Pyramid Lake from great storms. An elevation of 3,823 feet for Winnemucca Lake in 1867 seems reasonable and has been accepted in these studies.

A similar check on Pyramid Lake gives an area of about 220 square miles in 1867, which compares very favorably with the area estimated from Russell's survey in 1882 and from the General Land Office survey of 1911-12.

King reports a rise of 22 feet in Winnemucca Lake between 1867 and 1871. A further increase in depth of about ten feet occurred some time after 1871 and before 1882.

From photographs made by Russell, Professor J. C. Jones [8] determined the elevation of Pyramid Lake in 1882 to have been about 3,867 feet. The elevation of Winnemucca Lake in 1882, which from Russell's measurements was 12 feet lower than Pyramid Lake, was about 3,855 feet.

Basing his estimates on the recollections of Sutcliff of certain rocks which were laid bare by the recession of the Lake in 1889 and covered by the rising waters in 1890, Jones determined the elevations of Pyramid Lake to have been 3,861 feet in 1889 and 3,878 feet in 1890.

From certain records it would appear that Winnemucca Lake continued to rise after 1882 and reached a level in 1891 only five feet below Pyramid Lake. However, R. H. Cowles reports that Winnemucca Lake reached its highest level in the early 1880's. Mr. Cowles states that water from the Lake never reached the buildings at the headquarters of the ranch, which are located on Winnemucca Slough at an elevation of about 3,860 feet. The elevation of the highest recent beach-line on the shores of this Lake was determined in 1938 by instrument by E. P. Osgood, with the assistance of the writers, to be about 3,854.5 feet, which is likewise the elevation of the Lake given by Russell in 1882. About 1.5 feet below the highest beach-line is a white line, similar to the white line on the shores of Pyramid Lake.

Observations were made in 1938 by Mr. Osgood and the writers of conditions in the vegetation above and below the highest recent beach-line. The vegetation above this line differs markedly in color, in general appearance, and in greater age from that below this line. Parallel lines of bleached algae are found on many rocks from just below the beach-line at 3,854.5 feet downward for many feet, but no algae is found above this line. From all this evidence the writers have concluded that Winnemucca Lake did not exceed a level of about 3,855 feet in recent years.

Barriers of sawdust and of gravel are reported to have formed in Truckee River at its point of discharge into Pyramid Lake at intervals from the late 1870's to 1889, and to have caused a greater than normal portion of the runoff of Truckee River to flow to Winnemucca Lake. On the basis of precipitation-records, and of the portion of the discharge of Truckee River which should normally flow to Winnemucca Lake, it is estimated that Winnemucca Lake fell ten feet to an elevation of 3,845 feet between 1883 and 1889.

To prevent the continuation of excessive diversion of water to Winnemucca Lake to the detriment of Pyramid Lake, the Indian Service caused a tight brush-and-rock dam to be built across the mouth of Winnemucca Slough in the summer of 1888 or 1889. The presence of this dam changed the natural relationship between Pyramid and Winnemucca lakes and interfered with the normal overflow from Pyramid Lake to Winnemucca Lake. It may have been an influence in maintaining a high level in Pyramid Lake in 1890 and for several succeeding years. In February, 1891, the

Table 1--Significant recorded and interpolated elevations of Pyramid and Winnemucca lakes

Year	Pyramid Lake		Winnemucca Lake	
	Elevation[a]	Authority	Elevation[a]	Authority
	feet		feet	
1840	3860	Interpolated	3768	Interpolated from weather records
1844	3860	Fremont (sketch)	3768	Interpolated from Fremont
1854	....	.....	3772	Interpolated from Beckwith
1860	....	.....	3788	Interpolated from Buckland
1861	3865	Interpolated from weather records	....	.....
1862	3879	Interpolated from weather records	....	.....
1867	3867	Interpolated from King	3823	Interpolated from King
1868	3879	Interpolated from weather records	....	.....
1871	3876	After photo by King	3845	Interpolated from King
1882	3867	After photo by Russell	3855	Russell
1889	3862	Jones-Sutcliff	3845	Interpolated from weather records
1890	3878	Jones-Sutcliff	3855	Interpolated from weather records
1904	3862	U. S. Bureau of Reclamation	....	.....
1905	3867	Interpolated from weather records	....	.....
1908	....	.....	3844	Canterbury, U. S. Bureau of Reclamation
1909	3869	Southern Pacific Company	....	.....
1911	3865	U. S. General Land Office	3848	U. S. General Land Office
1917	3861	Jones-Sutcliff	....	.....
1922	3855	Southern Pacific Company	3822	Canterbury, U. S. Bureau of Reclamation
1926	3848	U. S. Bureau of Reclamation	3811	Canterbury, U. S. Bureau of Reclamation
1937	3818	Dukes	3775	Osgood
1938	3816	Dukes	3772	Osgood
1939	3818	Dukes	3768	Observations by writers

White line on Pyramid Lake at Pyramid Island	3873.0 feet[b]
Intermediate high water-mark at Pyramid Island	3876.0 feet[b]
Highest high water-mark at Pyramid Island	3879.0 feet[b]
White line on Winnemucca Lake at White Rocks	3853.5 feet[c]
High recent beach-line on Winnemucca Lake	3855.0 feet[c]

[a]Elevations given in nearest even foot.

[b]From instrument leveling from lake-surface by Venstrom, Hardman, Bray, and Russell, on December 19, 1939.

[c]From instrument leveling from G.L.O. bench-mark on west shore of Winnemucca Lake in N 1/2 sec.3, T. 24 N., R. 23 E., by Osgood, Venstrom, and Hardman on April 9, 1938.

Nevada legislature complained in a memorial to Congress [15] that, because of this dam, Winnemucca Lake was being deprived of water which would normally have flowed through Winnemucca Slough into this Lake. The dam was not maintained and deterioration soon destroyed much of its effectiveness.

A summary of the material gathered from historical records and other sources on the history of the two lakes is presented in the following paragraphs:

"Pyramid Lake was slightly below the overflow-level in 1844, and continued low until about 1860. A period of rather abundant moisture, accompanied by heavy floods in the Truckee River in 1862, 1868, and 1869, resulted in a high level which continued to 1871. The level for this year has been assumed by others from the records of King to have been about 3,885 feet but, from the evidence given above, it appears clear that the level in 1871 was not over 3,876 feet. Extreme high levels of 3,879 feet are assumed to have been reached in 1862 and 1868 or 1869. The Lake fell about 15 feet from an elevation of 3,876 feet in 1871 to an elevation of 3,861 feet in 1889, then is reported by Jones to have risen 17 feet, to 3,878 feet, in the year 1890. Pyramid Lake remained near the level of Winnemucca Slough until about 1917, since which time it has fallen rather steadily. The drop in the level of the two lakes was accelerated by the diversion of water to the Carson River Basin following the completion of

the Truckee Canal in 1907. In the drouth-period of the late 1920's and 1930's diversions for irrigation within and outside the basin took the great bulk of the total flows. The combined effect of declining river-flow and of increased irrigation-demands caused Pyramid Lake to drop about 50 feet from its normal level by the spring of 1938 to an elevation of 3,816 feet, which is the lowest point reached since its discovery in 1844.

"The rather scant and scattered records do not permit the reconstruction of the changes in Winnemucca Lake with as much accuracy as those for Pyramid Lake. Winnemucca Lake seems to have been at a very low level in 1844, and to have contained very little water until after 1860. The Lake apparently started to fill with the flood of 1862 and to have continued to gain until about 1882. During this period the Lake registered a gain of about 80 feet in depth. Winnemucca Lake is estimated to have lost about ten feet in depth from 1882 to 1889, which loss was regained from 1890 to 1893. Moderate fluctuations are noted from 1893 to about 1905. From 1905 to 1917 the Lake lost about 20 feet in depth, and after this date there began a steady downward trend which resulted in complete desiccation in 1939."

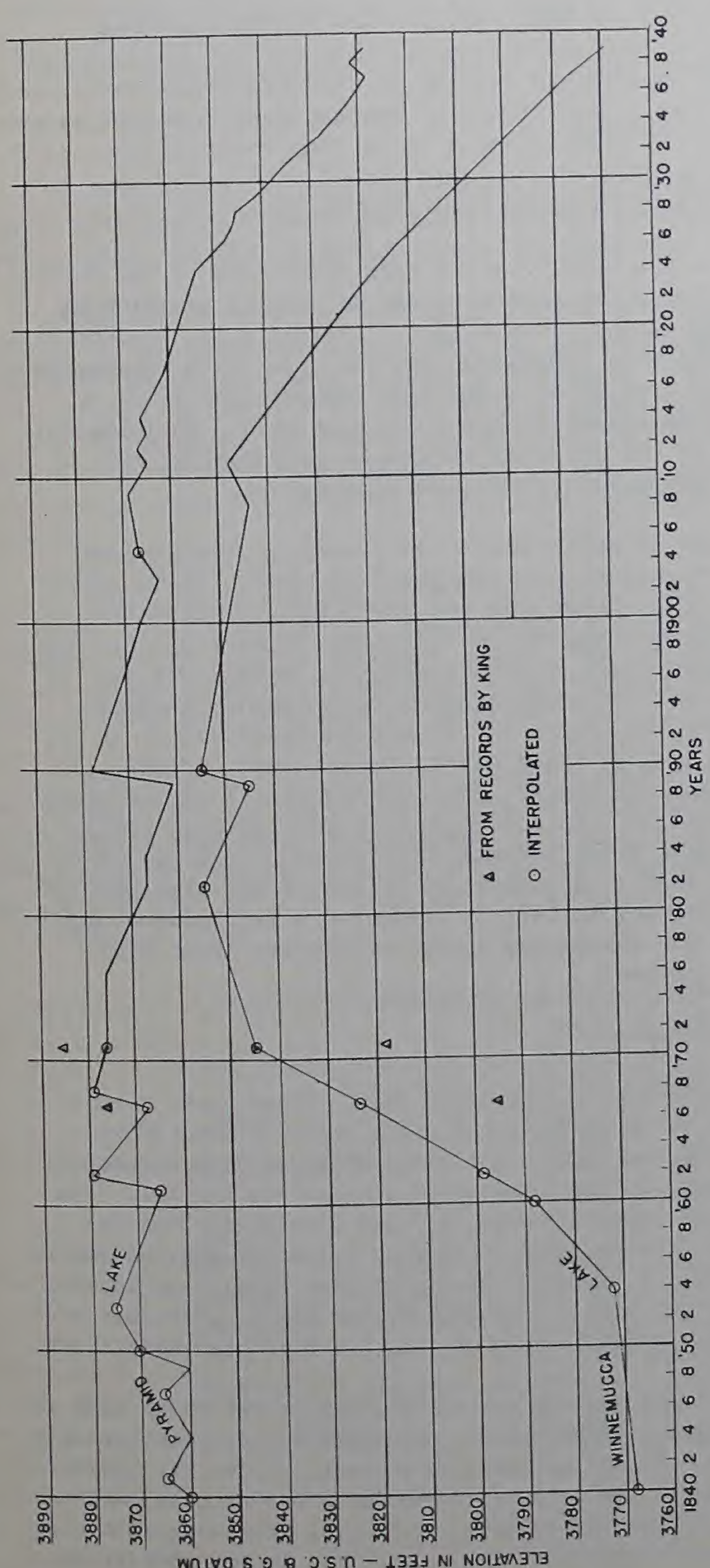

Fig. 3--Elevations of Pyramid and Winnemucca lakes

Some of the significant data on the elevations of the lakes are shown in Table 1 and Figure 3. Whenever known, the highest elevation for the year, which usually occurs following the spring runoff of Truckee River, has been given as the elevation for the year. Since evaporation consumes an equivalent of at least four feet in depth of water, a rather wide annual fluctuation in elevation of the Lake from this source alone can occur. When Pyramid Lake was high enough to permit backwater-discharge through Winnemucca Slough, large amounts of water were transferred to Winnemucca Lake. When evaporation-losses on Pyramid Lake were supplemented by losses by overflow, the elevation of the Lake could change many feet in a comparatively brief period of time.

Any attempt to illustrate graphically the relative conditions of water-supply as indicated by the levels of Pyramid and Winnemucca lakes is complicated by the presence of two lakes. One of these lakes is fed by direct flow from Truckee River and the other, while receiving some direct flow from the River, is fed in large part by overflow from the first lake. These natural conditions may permit a high level of water in Pyramid Lake without a corresponding and coincident high level in Winnemucca Lake. A high level of Pyramid Lake may mean only that a very high flood on Truckee River has occurred recently and that there has not been sufficient time for the surplus water in Pyramid Lake to drain out into Winnemucca Lake.

The quantities of water used within and diverted from the Truckee River Basin have had a very considerable influence on the inflow to Pyramid Lake, and, consequently, upon the behavior of both Pyramid and Winnemucca lakes. A further factor to be considered is the evaporation from Winnemucca Lake. Water-losses from this source

may vary from practically nothing when this Lake is dry to a very large amount when it is full.

When these conditions are considered, it seems to the writers that the total volume of water present in the lakes plus the losses occasioned by evaporation from Winnemucca Lake and from consumptive uses in the basin and diversions to points outside the basin is a more realistic measure of the condition of the lakes than is the elevation of Pyramid Lake or any combination of the elevations of Pyramid Lake with those of Winnemucca Lake.

The volume of the water-supply may be shown as total volumes of water in the lakes or as average annual runoff of Truckee River. A brief discussion of each of the various factors which enter into a computation of the total volumes of water credited to Pyramid and Winnemucca lakes is presented here.

Weather-records

Weather-records are available for the stations of San Francisco and Sacramento since 1849-50. Shingle Springs, with a record from 1849-50 to 1867-68, is used in this early period, while Nevada City has a continuous record from 1863-64 and is tied in with the record for Shingle Springs. This group of stations provides a long record of weather conditions for this area. There is a general relationship between the precipitation in the San Francisco-Sacramento Area and the precipitation east of the Sierra Nevadas; hence, this record can be used as a general index of moisture-conditions in the Truckee River Basin from 1850 to 1870.

Truckee River derives the major portion of its flow from the high elevations of the Sierra Nevada Range. For this reason the precipitation on the mountains may be used in deriving an index of the runoff of the River. Six stations [Auburn, Grass Valley, Nevada City, Placerville, Colfax, and Norden (Summit)] have long and relatively consistent records, and their records have sometimes been used for this purpose. They are located at elevations ranging from 1,200 to 6,000 feet on the west slope of the mountains and generally below the snow-belt. In a few instances in the early years the records of one or two stations seem to be inconsistent and, in this study, the records of those stations for those years have been disregarded.

While the precipitation on the high Sierras is reflected in the runoff of Truckee River with a marked degree of consistency in the great majority of the years of record, there appear to be instances in which the precipitation in the Sierras does not accurately indicate the runoff. It appears that in certain years the precipitation may be relatively heavier on the lower portion of the watershed than on the high mountains and in other years the reverse may be true. In an attempt to secure a more accurate measurement of precipitation on the entire watershed, another index was prepared. This index utilizes the record of the six Sierra stations, as discussed above, and of seven stations within the Truckee River Basin, namely, Reno, Truckee, Boca, Tahoe, Marlette Lake, Lewers Ranch, and Tamarack-Twin Lakes. The last station is in the Carson River Basin but is in the same general rainfall-belt. In some respects this index of precipitation seems to correlate with the runoff of Truckee River somewhat more closely than the record of the six Sierra stations and is used in this study. A comparison of this index with that portion of the San Francisco-Sacramento index subsequent to 1871-72 indicates a very general agreement and justifies the use of the latter index for estimating runoff of Truckee River from 1849-50 to 1870-71 (see Table 6 for these two indices).

Runoff-records

Continuous runoff-records of Truckee River are available since 1900. These records were taken at or near the State-Line Gaging-Station, which is near the point where Truckee River emerges from the mountains and is about midway on the stream and about 60 miles from Pyramid Lake. (This gaging-station is near the California-Nevada State-Line and derives its name from this fact; the actual gaging-point has been moved several times, but the discharges from the several points are comparable.) The portion of Truckee River Watershed below the gaging-station consists largely of low hills but in normal years it produces an appreciable runoff and in wet years it may make a substantial contribution to the total discharge of the River. Irrigation and diversion below the point of measurement have greatly modified the flows in the lower River.

Lake Tahoe, with its large evaporation area and restricted outlet, has a very pronounced effect upon the flows from this portion of the Truckee River Basin. In years of low precipitation and runoff, evaporation from the surface of the Lake may consume practically all of the inflow. On the other hand, the restricted outlet so reduces the rate of discharge from the Lake that not all the input in a very wet year can drain out during the current season and there may be a carry-over into the next year. For these reasons the runoff from Lake Tahoe is measured at its

point of discharge from the Lake and is subtracted from the total measured discharge from the Truckee River at State-Line. Hence, the recorded discharges of Truckee River at State-Line are exclusive of the runoff from the Lake Tahoe Basin.

In this study, the runoff-record of Truckee River since 1900, less the discharge from Lake Tahoe, as prepared by Harry C. Dukes [16], was used. A similar record of the natural flow of Lake Tahoe since 1924, calculated by Mr. Dukes, was used. In 1921 the California Department of Public Works [17] prepared an estimate of the runoff of Truckee River and Lake Tahoe in which the recorded discharges from the Lake since 1900 were corrected for storage. That portion of this record was used in this study (for the data used on runoff, see Table 6).

Runoff in the period from 1850 to 1871, as used in this study, was estimated by comparing the precipitation-index of the San Francisco Area with runoff-curves of Truckee River and Lake Tahoe as developed from the records since 1900. Runoff from 1872 to 1900 was estimated in a similar manner through the use of the index of precipitation developed for the Truckee River Basin. These estimates of runoff are given later in connection with the distribution of the volumes of water accumulated in Pyramid and Winnemucca lakes.

Consumptive use

Unquestionably, irrigation along the Truckee River, which began in the late 1850's, and diversions to points outside the Basin have had an influence on the behavior of Pyramid and Winnemucca lakes. In this paper an effort has been made to study the influence of these factors.

About 40,000 acres of land normally are irrigated in Truckee River Basin. This acreage shrinks in dry years and in dry periods, but the exact amount of shrinkage is unknown. It is believed that in this area an acre of irrigated land requires, on an average, about 2-1/2 acre-feet of water annually. (In this study consumptive use is defined as the total amount of water transpired by crops and evaporated from the surface of the ground covered by the crops. It does not include seepage-losses in the transportation of water to its point of use nor losses from percolation below the reach of plant-roots. Consumptive use is not synonymous with duty of water.)

In addition to the uses within the Basin, there have long been a number of small diversions to points outside the Basin. Losses from this source have been lumped in with the estimates of consumptive use within the Basin. Since 1907 the Truckee Canal, which leads from Truckee River to the Carson River Basin, has been a major factor in increasing the diversions of water of the Truckee River away from Pyramid Lake.

The consumptive use of water in the Truckee River Basin is estimated to have averaged 30,000 acre-feet per year from 1865 to 1871, 40,000 acre-feet from 1872 to 1882, 50,000 acre-feet from 1883 to 1889, 100,000 acre-feet from 1890 to 1917, and 75,000 acre-feet from 1918 to 1939. The diversions through the Truckee Canal were estimated to have averaged 200,000 acre-feet annually from 1907 to 1915, from which date recorded diversions were used. These data are shown in Table 2.

Table 2--Consumptive use and outside diversions of Truckee River water by periods

Period	Consumptive use and minor diversions		Truckee Canal diversions	Total consumptive use and diversions for periods
	Annual rate	Total	Total	
	acre-feet	acre-feet	acre-feet	acre-feet
1865-71	30,000	210,000	....	210,000
1872-82	40,000	440,000	....	440,000
1883-89	50,000	350,000	....	350,000
1890-1905	100,000	1,600,000	....	1,600,000
1906-17	100,000	1,200,000	2,172,000	3,372,000
1918-39	75,000	1,650,000	4,481,000	6,131,000
Totals		5,450,000	6,653,000	12,103,000

Evaporation

An estimate of evaporation from Pyramid and Winnemucca lakes is essential in arriving at any estimate of the total input of water into the lakes. In this study the evaporation from the lake-surfaces has been estimated on the basis of about 52 to 54 inches annually. This estimate was interpolated from various evaporation-records in the area and from the records of the fall in both Pyramid and Winnemucca lakes for several seasons. It is further assumed that, on an average, about 48 inches of the total amount of water evaporated was furnished to the lakes from the flow of Truckee River and the balance was supplied by direct precipitation on the water-surfaces and from the runoff of the areas immediately surrounding the lakes.

Variations in volumes of Pyramid and Winnemucca lakes

From the known and assumed levels of Pyramid and Winnemucca lakes, variations in volumes of water in the lakes have been computed. The volumes of the lakes were calculated from data given by Russell on his maps of the lakes in 1882. The area for Pyramid Lake from Russell's map was also checked by the General Land Office map of 1911-12. An area at an elevation of about 3,865 feet, which seems to be about normal for the Lake, of about 215 square miles, is used in this study. Normal seasonal fluctuations in this Lake made insignificant variations in its area.

As stated previously, the filling of Winnemucca Lake is assumed to have started following the floods of 1861-62 in the Truckee River. Since evaporation from Winnemucca Lake is a factor which must be considered in computing volumetric changes in the contents of the lakes an estimate of this item is given for each period of study. Winnemucca Lake receives some direct flow from Truckee River which is a factor in the period prior to 1850. Since 1918 the area of Winnemucca Lake has been decreasing rapidly and for this reason evaporation from this Lake has been calculated for each year in the period.

The changes in elevations and volumes were calculated for several periods, which were determined in large measure by the available records of lake-levels. The first period dates from 1839-40 to 1848-49, the second from 1849-50 to 1860-61, the third from 1861-62 to 1870-71, the fourth from 1871-72 to 1888-89, the fifth from 1889-90 to 1904-05, the sixth from 1905-06 to 1916-17, and the seventh from 1917-18 to 1938-39.

The data on variations in the volumes of the two lakes are shown in Table 3. The data on consumptive use was shown previously in Table 2. The volume of Pyramid Lake at an elevation of 3,865 feet, which is taken to be the usual or normal level, is about 25,500,000 acre-feet. Winnemucca Lake at its highest recorded level contained about 3,600,000 acre-feet.

Table 3--Changes in volume of Pyramid and Winnemucca lakes, evaporation from Winnemucca Lake, and consumptive use within and diversions to points outside Truckee River-Basin

Period	Pyramid Lake, changes in volume	Winnemucca Lake		Truckee River Basin, consumptive use within and diversions to outside
		Changes in volume	Average area during period	
	acre-feet	acre-feet	acres	acre-feet
1839-40 to 1848-49	....	....	......	....
1848-49 to 1860-61	+ 700,000	+ 400,000	19,200	....
1861-62 to 1870-71	+1,500,000	+2,400,000	52,480	210,000
1871-72 to 1888-89	-2,100,000	....	56,640	790,000
1889-90 to 1904-05	+ 800,000	....	55,680	1,600,000
1905-06 to 1916-17	- 852,000	- 500,000	51,200	3,372,000
1917-18 to 1938-39	-6,400,000[a]	-2,300,000	......	6,131,000

[a] 260,000 acre-feet retained in Lake Tahoe and Boca Reservoir at end of 1939 season were added to actual change in volume of Pyramid Lake.

Actual and calculated volumes of water in lakes

As mentioned previously, the natural relationships of Pyramid Lake and Winnemucca Lake are rather unusual. Also developments within the Truckee River Basin have greatly altered natural conditions of runoff. Under these conditions, variations in the calculated volumes of water in the lakes, which include consumptive use within the Basin and diversions to points outside the Basin, would seem to be a logical method of indicating changes in precipitation and runoff.

Table 4--Total actual volumes present and total calculated volumes of water in Pyramid and Winnemucca lakes, 1840 to 1939

Year	Actual volumes present	Calculated volumes
	thousands acre-feet	thousands acre-feet
1840	25,500	......
1850	25,500	......
1861	26,600	......
1862	28,870	......
1866	28,270	......
1868	31,000	......
1871	30,500	......
1882	30,070	30,595
1889	28,400	29,000
1890	30,000	30,600
1905	29,270	31,300
1917	27,900	32,800
1939	19,148	27,000

Based on the data given in Table 3, a calculation was made of the volumes of water which should have been present in Pyramid and Winnemucca lakes if natural conditions had remained undisturbed throughout the period from 1840 to 1939. The computations revealed that the calculated volumes of water would have been greater at times than were actually present at the highest recorded levels of the two lakes. It was assumed that the increase in volume would have been in Winnemucca Lake and an allowance has been made in the calculations for an increase in area and in evaporation from this Lake. The actual and calculated volumes are shown for selected years in Table 4 and on Figure 4.

A brief inspection of Table 4 and Figure 4 reveals that the total volume of water actually present in the lakes was greatest in 1868, but was only slightly less

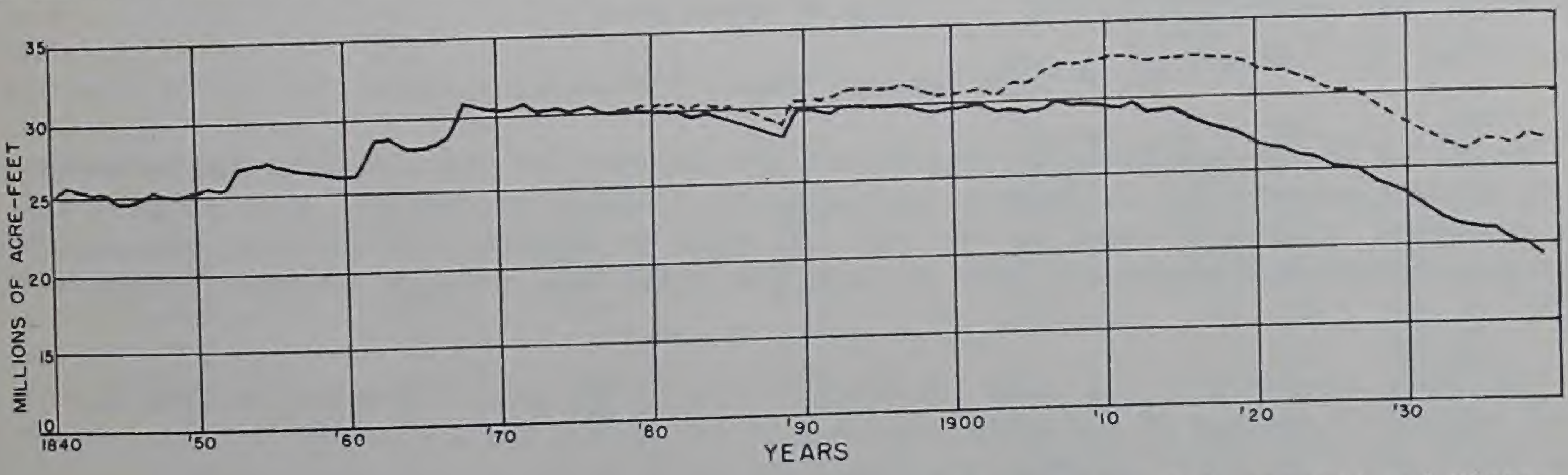

Fig. 4--Total actual and total calculated volumes of water present in Pyramid and Winnemucca lakes, 1840-1939 (Actual volumes shown by solid line, calculated volumes shown by dashed line)

in 1890. (The estimate of the level and volume of Pyramid Lake in 1868 is based largely upon weather records. These records indicate above-normal precipitation in 1866-67, extremely heavy precipitation and large floods in 1867-68, and heavy precipitation in 1868-69. Three years of above-normal precipitation tends to greatly increase the runoff from the watershed in the third year. Also excessive runoff into Lake Tahoe is not immediately discharged, because of the restricted outlet of the Lake, but is held over and becomes a part of the flow from the Lake in subsequent seasons. In view of these facts, it seems quite probable that Pyramid Lake continued to rise after 1868, and may have reached its highest elevation and greatest volume in 1869. A similar condition seems to have existed after 1890. It is entirely possible that the highest level in this period may have been reached in any one of the years 1890 to 1893.) By 1939, the volume of water actually present in the lakes was less by nearly 6,000,000 acre-feet than in 1840, and less by nearly 12,000,000 acre-feet than in 1868.

When the volumes of water artificially diverted from the Truckee River Basin and estimated to have been used within the Basin are added to the volumes actually present in the lakes, it is seen that in 1890 the total calculated volume was approximately equal to the volume present in 1868. By 1905 the calculated volume was greater than the actual volume in 1868 and the lakes continued to increase in volume, with minor fluctuations, and reached an all-time high about 1911. A high volume was maintained until about 1917, after which date the volume declined rapidly to about 1934. There has been a slight rise in the calculated volume since 1934.

From Table 4 and Figure 4 it would also appear that the total calculated volume of water in Pyramid and Winnemucca lakes was slightly greater in 1939 than the estimated actual volume in 1840 and was about equal to the actual volume present in 1861. If the total calculated volume present in 1939 is credited to Pyramid Lake, this Lake would stand at an elevation of approximately 3,872 feet, or slightly above a normal level. However, when Pyramid Lake is near a normal level direct flow from Truckee River to Winnemucca Lake can take place under undisturbed natural

Table 5--Total calculated increment to lakes in thousands of acre-feet by periods 1839-40 to 1938-39

Period	Pyramid Lake		Winnemucca Lake		Consumptive use and diversions	Total calculated increment to lakes
	Volume-change	Total evaporation	Volume-change	Total evaporation		
1839-40 to 1848-49	.....	5,440	.....	200	.....	5,640
1849-50 to 1860-61	+ 700	6,528	+ 400	460	.....	8,088
1861-62 to 1870-71	+1,500	5,440	+2,400	1,820	210	11,370
1871-72 to 1888-89	-2,100	9,792	.....	4,080	790	12,562
1889-90 to 1904-05	+ 800	8,704	.....	3,560	1,600	14,664
1905-06 to 1916-17	- 852	6,580	- 500	2,450	3,372	11,050
1917-18 to 1938-39	-6,400	10,560	-2,300	2,800	6,131	10,791

conditions and not all of the calculated discharge of Truckee River in the 22 years since 1918 would have been delivered to Pyramid Lake. It is estimated that under natural conditions and with no obstructions in Winnemucca Slough at least 1,000,000 acre-feet of the flow of Truckee River in this period would have been diverted to Winnemucca Lake. From these considerations, it is concluded that by 1939 Pyramid Lake would have fallen to an elevation of about 3,864 feet and Winnemucca Lake would have receded to a depth of about 25 feet.

Calculated seasonal runoff of Truckee River

As stated in the introduction, long records of the flows of the streams in Nevada which supply irrigation-water are of interest and value for a number of reasons. Such a record has been developed for Truckee River for the past 100 years by distributing the total calculated increment to Pyramid and Winnemucca lakes as developed above into seasonal (October to September) runoff.

The total increment to the lakes (as derived from an estimate of evaporation from the two lakes, changes in volumes of the lakes, consumptive use within the Truckee River Basin, and diversions to points outside the Basin) is summarized in Table 5.

The periodic increments to the lakes from Table 5 were distributed by means of indices into yearly seasonal runoff of Truckee River. These indices of distribution, which are the yearly seasonal discharges of the River calculated as percentages of the average seasonal runoff, were prepared from the best available data. For the period 1839-40 to 1849-50 there are no records of runoff of the River nor of precipitation from which it can be estimated. There are, however, a number of references in the literature of this time to climatic conditions, such as floods, deep snows, and drouths, which give indications of probable stream-runoff, and these were used in preparing an index of distribution.

From 1849-50 to 1870-71 the precipitation-records of the San Francisco, Sacramento, Shingle Springs, and Nevada City weather-stations were used in estimating the yearly runoff of Truckee River. The relationship between the precipitation as shown by these stations and that shown by stations within and adjacent to the Truckee River Basin was discussed previously in this paper. The distribution-index for this period is believed to be fairly accurate.

The runoff of Truckee River for the years from 1871-72 to 1899-1900 was estimated from a precipitation-index developed for the Truckee River Basin as previously described. The distribution-index should be quite accurate.

For the period from 1900-1901 to 1938-39, the measured runoff of Truckee River at the State-Line Gaging-Station, plus the runoff of Lake Tahoe at its outlet, was used in preparing the index of distribution. This index should be very accurate.

The data on the several precipitation-indices, the runoff of Truckee River and Lake Tahoe at State-Line from runoff and precipitation-records, and the runoff of Truckee River at Pyramid Lake in acre-feet and in percentages of average runoff are shown in Table 6. The runoff of the River in percentages of average runoff is shown in Figure 5.

These data are also summarized by periods in Table 7.

Table 6--Truckee River Basin precipitation-index, seasonal runoff in acre-feet (estimated and recorded) and in percentage of average of Truckee River and Lake Tahoe, and estimated seasonal runoff from Lake records in acre-feet and in percentage of average runoff 1839-40 to 1938-39

Year	Truckee River Basin precipitation-index	Percentage runoff, Lake Tahoe	Estimated runoff, Lake Tahoe	Percentage runoff, Truckee River at State Line gaging-station minus Tahoe	Estimated runoff, Truckee River minus Tahoe	Estimated total runoff, Truckee River plus Tahoe	Seasonal runoff from Lake records	Percentage average, seasonal runoff
			acre-feet		acre-feet	acre-feet	acre-feet	
1839-40[a]	...	...	....	...	....	....	1,128,000	152
1840-41	...	...	....	...	....	....	282,000	38
1841-42	...	...	....	...	....	....	677,000	91
1842-43	...	...	....	...	....	....	225,000	30
1843-44	...	...	....	...	....	....	338,000	46
1844-45	...	...	....	...	....	....	395,000	53
1845-46	...	...	....	...	....	....	395,000	53
1846-47	...	...	....	...	....	....	1,128,000	152
1847-48	...	...	....	...	....	....	395,000	53
1848-49	...	...	....	...	....	....	677,000	91
1849-50[b]	151	284	512,000[b]	200	790,000[b]	1,302,000[b]	1,616,000	218
1850-51	39	...	....	15	59,000	59,000	74,000	10
1851-52	91	60	108,000	81	319,000	427,000	532,000	72
1852-53	164	356	644,000	240	947,000	1,591,000	1,975,000	267
1853-54	102	84	152,000	100	394,000	546,000	680,000	92
1854-55	88	55	100,000	76	300,000	400,000	498,000	67
1855-56	75	30	54,000	58	229,000	289,000	360,000	48
1856-57	73	30	54,000	55	217,000	271,000	336,000	45
1857-58	77	30	54,000	61	241,000	295,000	366,000	49
1858-59	93	65	117,000	84	331,000	448,000	558,000	75
1859-60	99	78	141,000	94	371,000	512,000	637,000	86
1860-61	85	48	87,000	71	280,000	367,000	456,000	62
1861-62	215	650	1,118,000	400	1,580,000	2,698,000	3,259,000	440
1862-63	63	10	18,000	43	170,000	188,000	442,000	60
1863-64	48	...	....	25	99,000	99,000	119,000	16
1864-65	109	100	180,000	110	434,000	614,000	789,000	108
1865-66	105	95	79,000	104	410,000	489,000	629,000	85
1866-67	149	270	487,000	195	770,000	1,257,000	1,612,000	217
1867-68	192	560	1,014,000	360	1,420,000	2,434,000	2,923,000	394
1868-69	99	78	141,000	94	371,000	512,000	858,000	116
1869-70	85	50	90,000	71	280,000	370,000	475,000	64
1870-71	66	16	27,000	46	181,000	210,000	264,000	36
1871-72[c]	118	135	244,000[c]	121	478,000[c]	722,000[c]	1,108,000	149
1872-73	68	20	36,000	48	189,000	225,000	348,000	47
1873-74	110	100	180,728	111	438,000	619,000	954,000	129
1874-75	77	35	63,600	60	237,000	301,000	466,000	63
1875-76	125	160	289,000	139	548,000	837,000	1,295,000	175
1876-77	59	10	18,000	38	189,000	207,000	320,000	43
1877-78	93	65	117,500	84	331,000	448,000	695,000	94
1878-79	96	70	126,600	89	351,000	478,000	740,000	100
1879-80	119	140	253,000	128	505,000	758,000	1,176,000	159
1880-81	99	80	144,600	94	371,000	516,000	798,000	108
1881-82	101	87	147,400	98	386,000	533,000	825,000	111
1882-83	72	22	39,800	54	213,000	253,000	392,000	53
1883-84	118	135	244,000	127	502,000	746,000	1,155,000	156
1884-85	75	30	54,100	58	229,000	283,000	438,000	59

Table 6--Truckee River Basin precipitation-index, seasonal runoff in acre-feet (estimated and recorded) and in percentage of average of Truckee River and Lake Tahoe, and estimated seasonal runoff from Lake records in acre-feet and in percentage of average runoff 1839-40 to 1938-39--Continued

Year	Truckee River Basin precipitation-index	Percentage runoff, Lake Tahoe	Estimated runoff, Lake Tahoe	Percentage runoff, Truckee River at State Line gaging-station minus Tahoe	Estimated runoff, Truckee River minus Tahoe	Estimated total runoff, Truckee River plus Tahoe	Seasonal runoff from Lake records	Percentage average seasonal runoff
			acre-feet		acre-feet	acre-feet	acre-feet	
1885-86	110	100	180,728	96	279,000	460,000	712,000	96
1886-87	81	40	72,300	51	201,000	273,000	422,000	57
1887-88	65	15	27,100	45	177,000	204,000	316,000	43
1888-89	73	24	43,400	55	217,000	260,000	402,000	54
1889-90	186	484	876,000	316	1,246,000	2,122,000	2,366,000	319
1890-91	91	60	108,500	81	320,000	428,000	718,000	97
1891-92	91	60	108,500	81	320,000	428,000	518,000	70
1892-93	155	320	578,000	211	832,000	1,410,000	1,705,000	230
1893-94	104	82	148,400	103	406,000	554,000	670,000	90
1894-95	125	160	289,000	139	548,000	837,000	1,012,000	136
1895-96	118	135	244,000	121	477,000	721,000	872,000	118
1896-97	112	105	190,000	115	454,000	644,000	778,000	105
1897-98	69	20	36,000	50	197,000	233,000	282,000	38
1898-99	91	60	108,500	81	319,000	427,000	518,000	70
1899-00	111	106	192,000	113	446,000	638,000	772,000	104
1900-01[d]	126	160	289,600[d]	146	575,818[d]	865,418[d]	1,048,000	141
1901-02	97	90	163,400	106	418,566	581,966	705,000	95
1902-03	95	82	148,200	93	364,902	513,100	622,000	84
1903-04	130	285	514,300	191	754,288	1,268,588	1,532,000	207
1904-05	98	57	102,300	88	348,266	450,566	546,000	74
1905-06	130	295	532,500	159	625,150	1,157,650	1,304,000	178
1906-07	161	411	742,900	189	745,500	1,488,400	1,679,000	226
1907-08	70	42	75,400	75	297,000	372,400	419,000	57
1908-09	125	223	402,600	149	588,094	990,694	1,118,000	151
1909-10	98	155	280,100	118	464,872	744,972	839,000	113
1910-11	145	255	462,200	182	716,905	1,179,105	1,331,000	179
1911-12	56	29	53,000	55	218,979	271,979	305,000	41
1912-13	70	31	56,200	65	258,139	314,339	353,000	48
1913-14	129	259	468,600	177	697,998	1,166,598	1,318,000	178
1914-15	94	70	127,300	102	401,637	528,937	596,000	80
1915-16	114	178	320,300	155	609,902	930,202	1,049,000	142
1916-17	93	127	229,200	109	428,238	657,438	741,000	100
1917-18	73	49	88,800	66	260,171	348,971	415,000	56
1918-19	101	25	45,400	121	477,878	523,278	627,000	85
1919-20	76	4	7,300	59	231,451	238,751	283,000	38
1920-21	114	101	182,000*	101	397,913	579,913	693,000	93
1921-22	113	111	200,000*	119	467,098	667,098	796,000	107
1922-23	108	97	175,938*	88	344,744	520,682	622,000	84
1923-24	49	82	147,750*	23	91,635	239,385	275,000	37
1924-25	92	49	89,361[d]	76	299,069	388,430	463,000	62
1925-26	77	37	66,874	54	212,426	279,300	332,000	45
1926-27	116	73	131,187	140	553,032	684,219	817,000	110
1927-28	87	87	156,616	87	343,149	499,765	597,000	80
1928-29	61	7	12,228	47	183,866	196,094	233,000	31
1929-30	85	9	17,133	75	295,316	312,449	371,000	50

Table 6--Truckee River Basin precipitation-index, seasonal runoff in acre-feet (estimated and recorded) and in percentage of average of Truckee River and Lake Tahoe, and estimated seasonal runoff from Lake records in acre-feet and in percentage of average runoff 1839-40 to 1938-39--Concluded

Year	Truckee River Basin precipitation-index	Percentage runoff, Lake Tahoe	Estimated runoff, Lake Tahoe	Percentage runoff, Truckee River at State Line gaging-station minus Tahoe	Estimated runoff, Truckee River minus Tahoe	Estimated total runoff, Truckee River plus Tahoe	Seasonal runoff from Lake records	Percentage average seasonal runoff
			acre-feet		acre-feet	acre-feet	acre-feet	
1930-31	64	1	940	33	128,667	129,607	154,000	21
1931-32	106	9	16,341	95	373,299	389,640	466,000	63
1932-33	63	2	3,253	51	202,239	205,492	244,000	33
1933-34	75	1	1,623	32	124,771	126,394	150,000	20
1934-35	105	5	9,080	92	364,221	373,301	495,000	59
1935-36	123	74	133,398	108	424,602	558,000	667,000	90
1936-37	101	69	124,670	75	294,744	419,414	503,000	68
1937-38	147	191	346,566	189	745,908	1,092,474	1,303,000	176
1938-39	65	74	133,463	37	147,422	280,885	335,000	45

[a]No precipitation-records are available for the years 1839-40 to 1848-49, hence no estimate of runoff on the basis of precipitation-records is possible.

[b]Estimates of runoff of Lake Tahoe and Truckee River minus Tahoe in the period from 1849-50 to 1870-71 are based on the San Francisco-Sacramento area precipitation-index.

[c]Estimates of runoff of Lake Tahoe and Truckee River minus Tahoe in the period from 1870-71 to 1899-1900 are based on the Truckee River Basin precipitation-index, as described previously.

[d]From 1900-1901 the recorded flows of the Truckee River minus Lake Tahoe from the records of Harry C. Dukes, Water Master, were used. Mr. Dukes' record for the natural flow of Lake Tahoe from 1924-25 to 1938-39 was also used. From 1900-01 to 1920-21 the recorded flows of Lake Tahoe, corrected for storage in the Lake, as given on page 305 of Bulletin No. 5 of the California Department of Public Works were used.

*Estimated by writers.

The 100-year average seasonal runoff of Truckee River at Pyramid Lake, as calculated from the record of changes in the levels and volumes of Pyramid and Winnemucca lakes, is about 741,000 acre-feet. This exceeds the 90-year average seasonal runoff of the River at the State-Line Gaging-Station of 605,000 acre-feet, as estimated from precipitation-records or as actually recorded, by about 136,000 acre-feet. A considerable part of this difference is undoubtedly accounted for by the fact that the gaging-point for the runoff-records of Truckee River is located about midway on the stream and a portion of the normal discharge of the stream is not included in these measurements.

Norcross [18] estimated that the consumptive use of water on the Truckee Meadows during the period 1907-08 to 1918-19 averaged about 72,000 acre-feet per year. For this same period, which was somewhat above normal in precipitation and stream-runoff, the discharge of the Truckee River at Vista, at the lower end of the Meadows, averaged about 8,000 acre-feet more than the discharge at the State-Line Gaging-Station. In addition to the estimated 72,000 acre-feet used on the Truckee Meadows considerable quantities of water were used in the Washoe Valley and along Galena and Steamboat creeks and some water was lost to Truckee River through diversions to points outside the Basin. Under natural conditions all of this water would have reached Pyramid Lake. There are undoubtedly contributions to the stream in the 40-mile section between Vista and the mouth of the River which would tend to increase the difference in the quantity of water as measured at State-Line and as discharged into Pyramid Lake. It seems probable that this difference may average as much as 100,000 or more acre-feet.

A factor which must be considered in relating the changes in the volumes of water contained in Pyramid and Winnemucca lakes to discharges of Truckee River is the item of yearly variations in the amount of direct rainfall on the surface of the lakes and of inflow from the watershed immediately adjacent to the lakes. Direct precipitation might vary from considerably less than five inches to as much as eight or more inches. There is no possible measure of the direct runoff from the immediately adjacent watershed, but there can be no doubt that the contributions

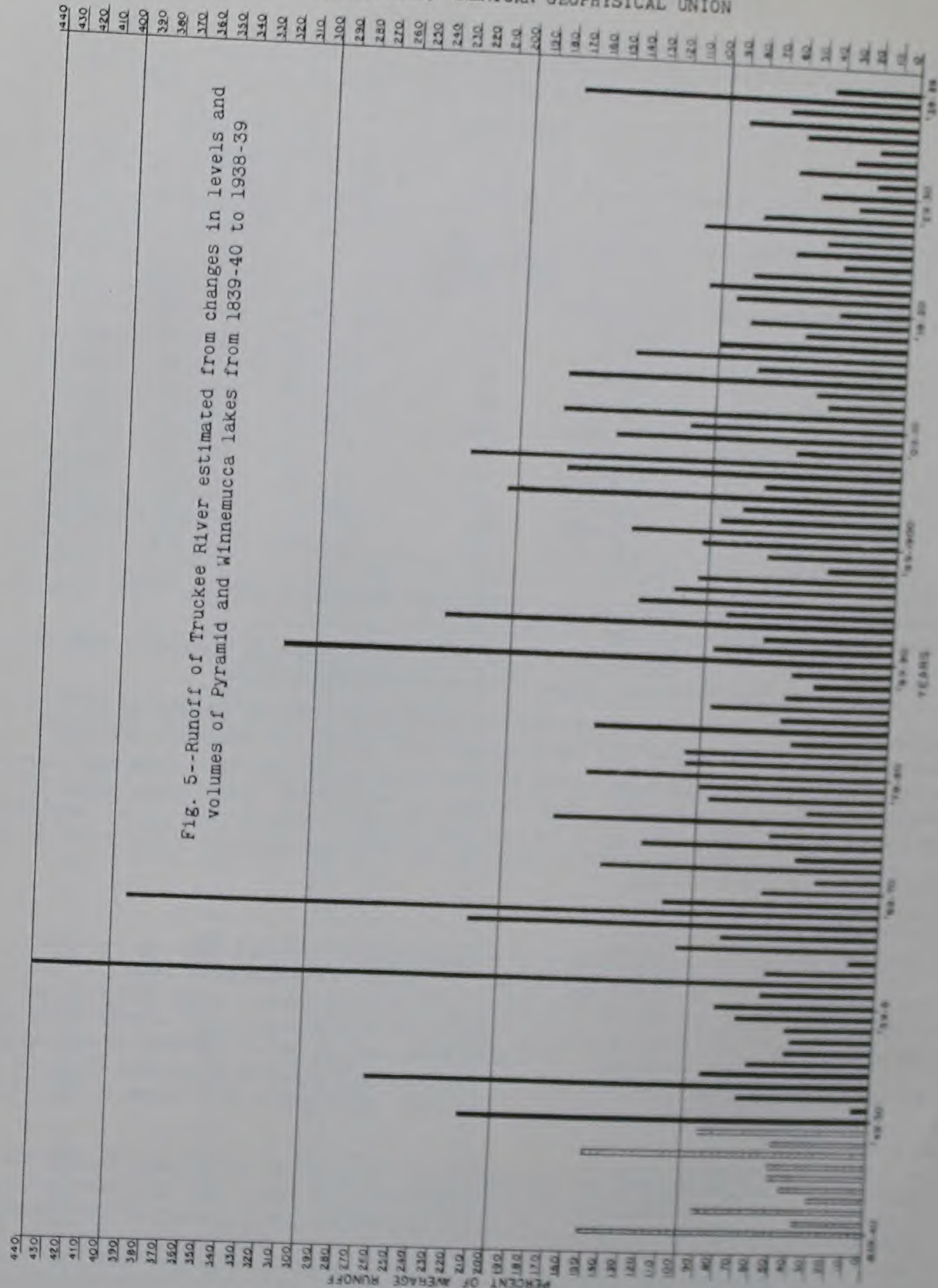

Fig. 5--Runoff of Truckee River estimated from changes in levels and volumes of Pyramid and Winnemucca lakes from 1839-40 to 1938-39

from this source vary with fluctuations in the rainfall over the area. While the variations in the contributions to the lakes from these two sources are undoubtedly real, the contributions themselves constitute such a small proportion of the total inflow to Pyramid Lake that they do not appear to have any particular significance in this study.

It is also possible that the estimates of outside diversions, except those through the Derby Canal, of consumptive use in the Basin of the areas of Pyramid and Winnemucca lakes, or of the rate of evaporation from the lakes may have been too high. An overestimation of any of these factors would tend to increase the calculated contribution of water from the Truckee River to the lakes. A reduction of two inches in the estimated rate of evaporation would reduce the estimated yearly runoff by 30,000 acre-feet. However, the estimates of inflow to Pyramid and Winnemucca lakes appear to be within reasonable limits, and any miscalculations which may exist do not have any effect upon the percentage or relative values shown in the chart of seasonal

Table 7--Total discharge and average yearly runoff of Truckee River at State Line and at Pyramid Lake by periods, 1849-50 to 1938-39

Period	Length, years	Estimated discharge of Truckee River at		Estimated average seasonal runoff of Truckee River at	
		State Line	Pyramid Lake	State Line	Pyramid Lake
1839-40 to 1848-49	10	....	5,640,000	....	564,000
1849-50 to 1860-61	12	6,507,000	8,088,000	542,000	674,000
1861-62 to 1870-71	10	8,871,000	11,370,000	887,000	1,137,000
1871-72 to 1888-89	18	8,123,000	12,562,000	451,300	698,000
1889-90 to 1904-06	16	12,121,000	14,664,000	757,600	916,500
1905-06 to 1916-17	12	9,802,000	11,050,000	816,800	920,800
1917-18 to 1938-39	22	9,052,000	10,791,000	411,500	490,500
Total	100	54,476,000[a]	74,165,000	....	....
Average	...	....	....	605,300[a]	741,650

[a]For 90 years only.

flows. If the average discharge of Truckee River at Pyramid Lake of 741,600 acre-feet from these estimates is reduced by about 100,000 acre-feet to correct for inflow below the State-Line Gaging-Point, the resultant figure of about 641,000 acre-feet may represent fairly accurately the average yearly runoff for the past 100 years at that gaging-station.

Summary

Pyramid and Winnemucca lakes receive and evaporate the waters of Truckee River, hence fluctuations in the levels and volumes of the lakes afford a means of measuring variations in the volume of water discharged into the lakes by Truckee River. The history of the fluctuations in the lake-levels and volumes from the discovery of Pyramid Lake in 1844 by Captain Fremont to 1939 is traced in this study.

The problem is complicated by the fact that a considerable part of the runoff of Truckee River has been used for irrigation within the Basin or diverted to points outside it. These deductions from the quantities of water which would have reached Pyramid Lake under natural conditions have been calculated and added to the volumetric changes in the lakes.

These studies indicate that Pyramid Lake was slightly below a normal level in 1844, and that presumably in 1840 Winnemucca Lake was almost, if not entirely, dry. Volumetrically the lakes were at a very low level and remained relatively low until about 1860.

The volume of water in the two lakes increased rapidly in the years 1862 to 1871 and decreased slightly from 1882 to 1889. With the very wet year of 1889-90 there began a moist period which lasted until about 1917. Pyramid and Winnemucca lakes, without consumptive use and outside diversions, would have reached the highest point in volume in the period of study about 1911, and would have maintained this high volume until about 1917.

After about 1917 the volume of water in the lakes declined and by 1936 would have reached a point where the volume was only slightly greater than in 1840. There has been a slight increase in volume since 1936.

A record of runoff of Truckee River for the period of study was prepared by distributing the volumes of water in the lakes into annual seasonal discharges.

The general conclusions from this study are:

(1) That drouth-conditions prevailed on the Truckee River Watershed for many years prior to 1840.
(2) That a period of greatly increased precipitation began about 1860 which, although broken with minor drouth-periods of short duration, lasted until about 1917.
(3) That since 1917 a drouth-period, comparable in intensity but not in duration to the period prior to 1840, has existed.
(4) That the period from 1860 to 1917, and particularly that portion of the period which began in 1890, was unusually moist for this area.

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SOME FACTORS OF THE HYDROLOGY OF THE SIERRA NEVADA FOOTHILLS

P. B. Rowe

Introduction

The purpose of this paper is to discuss briefly some factors of the hydrology in the Sierra Nevada foothills of the San Joaquin Basin. The data presented are primarily concerned with the hydrologic phases of a study started by the Forest Service at North Fork, California, in 1929 to determine the influence of the woodland-chaparral vegetation on water-yield, surface-runoff, and erosion. [A complete discussion of the experimental results of the North Fork study is contained in a manuscript by P. B. Rowe, "Influence of woodland-chaparral vegetation on soil-water relations," submitted March 1940 for publication as a U. S. Dept. Agric. Tech. Bull.]

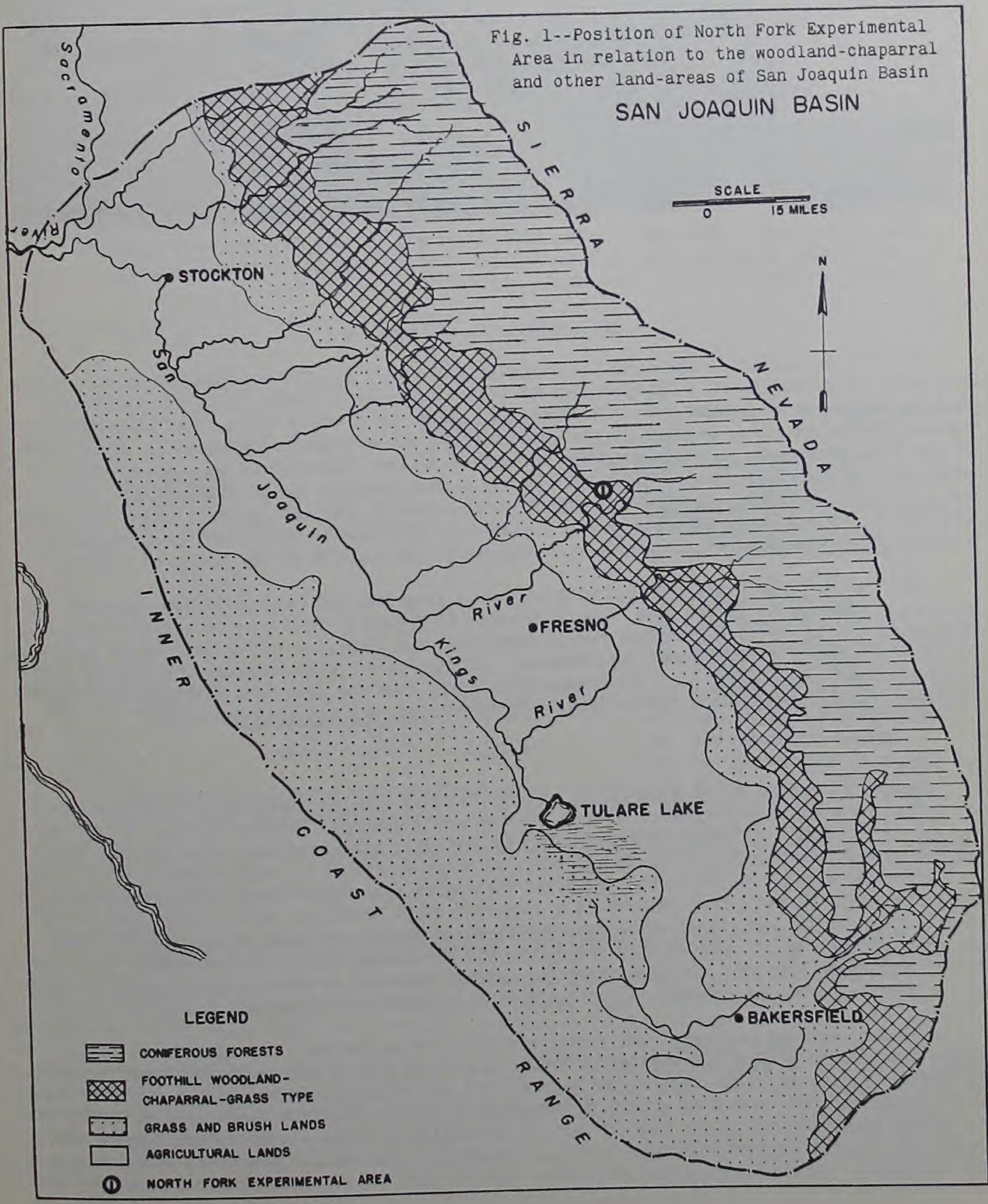
The experimental area (Fig. 1) is centrally situated in the upper reaches of the woodland-chaparral-grass type of the Sierra Nevada foothills. This type extends in a narrow belt along the western slope of the Sierra Nevada between elevations of 1,000 and 3,000 feet and covers approximately 2,500,000 acres, or more than 20 per cent of the total watershed-acreage of the San Joaquin Basin. This area was selected for the study because of its importance in local water-production and because it contributes materially to some of the serious floods occurring in the region.

Physical factors

The climate at North Fork is Mediterranean in type, characterized by moderate temperature, an annual precipitation ranging from 14 to as much as 60 inches and averaging about 33 inches, and a summer deficiency of rainfall. The soil is a residual, immature, sandy clay-loam derived from the normal weathering of a granodiorite parent-rock formation. It is easily erodible and averages about 36 inches in depth.

Typical tree- and shrub-vegetation of the experimental area (Fig. 2) includes an overstory of scattered Digger pine (*Pinus sabiniana*) and California black oak (*Quercus kelloggii*) and an understory composed of such species as buckeye (*Aesculus californica*), deerbrush (*Ceanothus integerrimus*), buckbrush (*Ceanothus cuneatus*), interior live-oak (*Quercus wislizenii*), birch-leaf mountain mahogany (*Cercocarpus betuloides*), and poison-oak (*Toxicodendron diversilobum*). Under and in the interspaces between the tree- and shrub-vegetation are numerous herbaceous species, such as mules-ears (*Wyethia elata*), tarweed (*Madia elegans*), and gamble weed (*Sanicula spp.*), and various grass-species consisting largely of annual bromes and fescues. The vegetation on the experimental area is more representative of the chaparral-woodland at its higher elevation, the upper limits of the Sonoran life zone, than of the type as a whole. It contains a much higher proportion of the more mesophytic species than is found in the type at lower elevations.

Fig. 1--Position of North Fork Experimental Area in relation to the woodland-chaparral and other land-areas of San Joaquin Basin



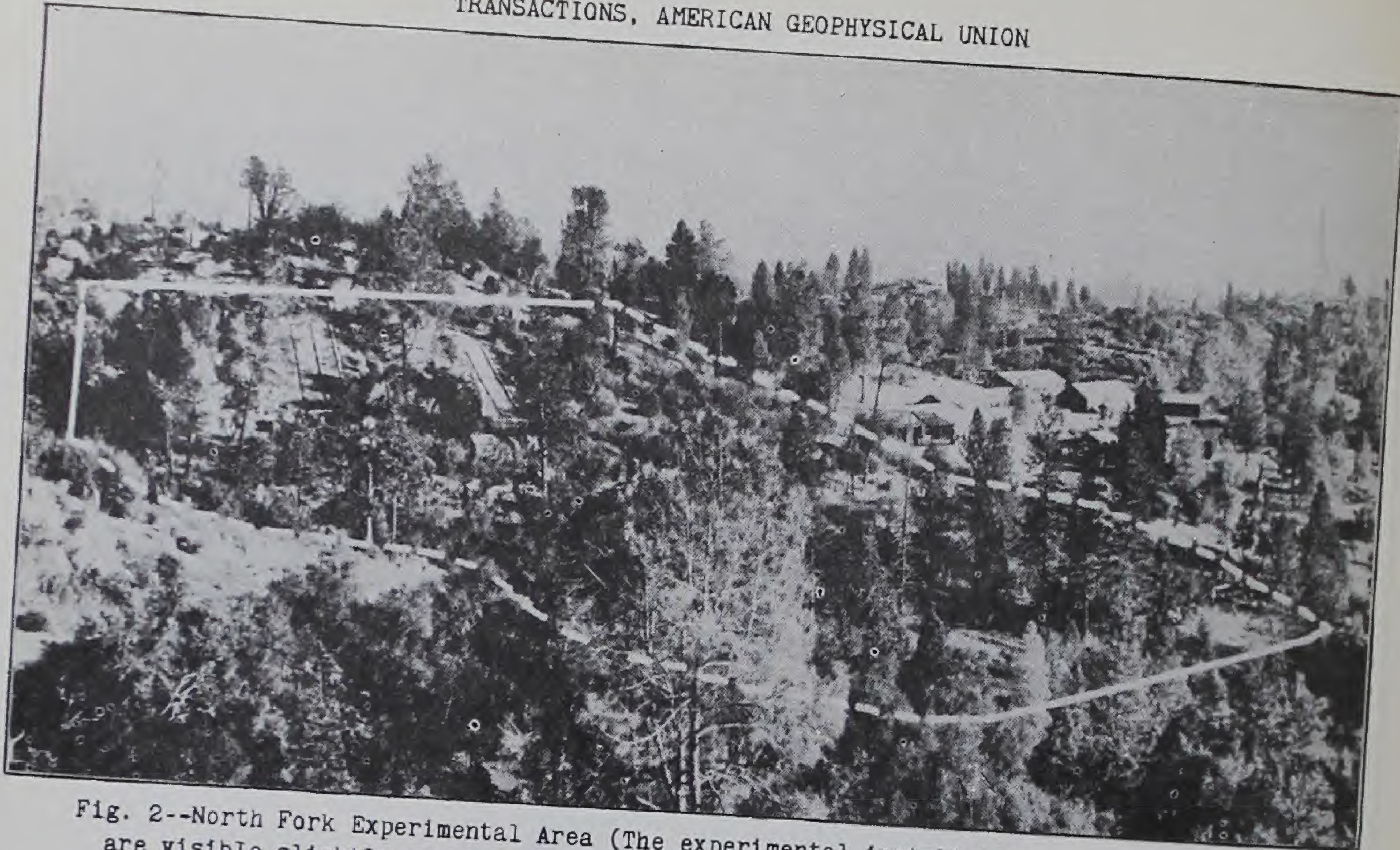


Fig. 2--North Fork Experimental Area (The experimental installations, some of which are visible slightly above left center, are for the most part situated beyond direct influence of pine-trees shown in Figure)

Instrumentation and methods

The instrumentation employed in the study is shown in Figure 3. It includes three pairs of 1/40-acre and two pairs of 1/100-acre surface-runoff and erosion plots, three soil-moisture sampling-areas, eight lysimeters, 16 interception-gages, 29 stemflow units, four snow-stations, a soil-temperature pit, a weather-station, and various meteorological instruments. On one pair of the 1/40-acre plots the vegetation was maintained without disturbance; on a second pair the vegetation on the plots and the border-strips was burned annually except for one year, 1930; and on a third pair the vegetation was burned twice--once in 1930 and again in 1936. The 1/100-acre plots, soil-moisture sampling-areas, lysimeters, interception-units, and meteorological instruments were maintained and operated to supplement the results of the 1/40-acre plots.

The 1/40-acre plots are ten feet wide and 108.9 feet long and have a westerly exposure and an average gradient of 32 per cent. As illustrated in Figure 4, each plot is equipped with a tipping bucket for recording surface-runoff rates and with apparatus for collecting and measuring the total volume of surface-runoff and erosion. As the runoff passes through the tipping bucket it is recorded electrically on a continuous-strip chart-recorder that also automatically registers such factors as rainfall-intensities, wind-velocities, and interception-rates.

Results

Changes in vegetation as a result of burning--Burning and the depletion of soil-nutrients by runoff and erosion have greatly altered the vegetation-complex. Before burning, the spring density of the tree- and shrub-cover was about 50 per cent, the herbaceous cover ten per cent, and the litter-cover approximately 58 per cent. As shown ~~in~~ Figure 5, these formed a total cover of approximate density 75 per cent. The first burning of the vegetation on both the annually and periodically burned plots resulted in a reduction of 50 to 55 per cent in total vegetation-cover. This was the net result of an increase of 35 to 45 per cent in herbaceous cover and a decrease of about 80 per cent in both the shrub- and the litter-cover. By the second spring after the burning, however, the density of the vegetation had returned to within approximately 28 per cent of normal as a result of the rapid reestablishment of the shrub- and litter-cover.

With the repeated burning of the vegetation there was a continual decrease in both the growth-rate and density of the vegetation and in the proportion of grasses to weed-species until by 1938 approximately 90 per cent of the mineral soil was exposed. On the once-burned plots the total density of the vegetation gradually increased following the first burn until by 1936 it was within approximately 16 per cent of that of the undisturbed plots. The second burning of these plots in the fall of 1936 resulted in a much greater decrease in the growth and density of the vegetation, particularly in the herbaceous species, and the reestablishment of the cover was

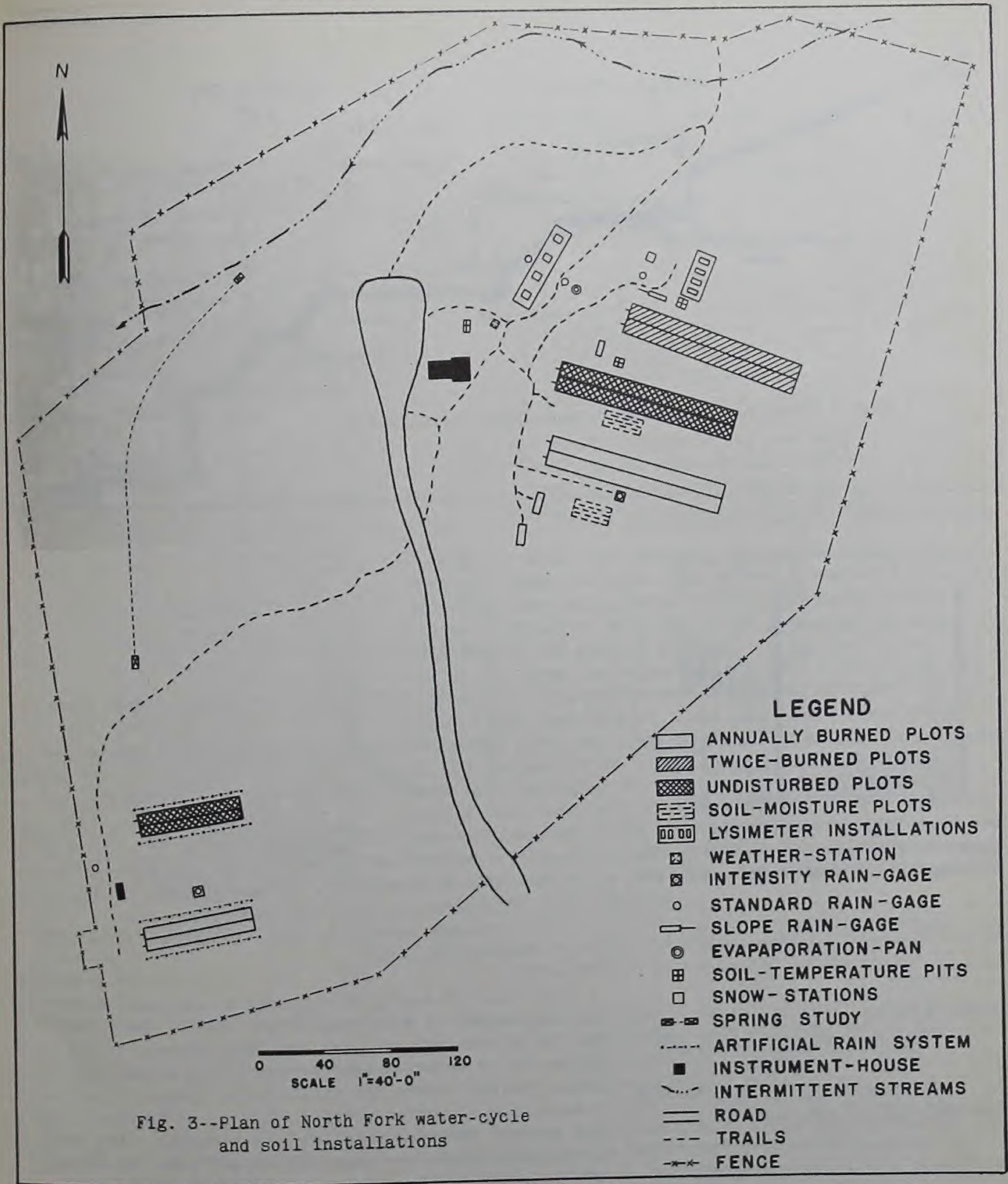


Fig. 3--Plan of North Fork water-cycle and soil installations

much slower than after the first burn.

Influence of burning measured in terms of surface-runoff and erosion--One of the most apparent results of burning was the increase in surface-runoff and erosion. (The term "surface-runoff" as used in this article refers only to that portion of the runoff which flows entirely over the surface of the ground and should not be confused with total discharge.) In considering the measurements of total runoff and erosion, however, it should be borne in mind that they are the results of plot-studies. The measurements of total surface-runoff if applied quantitatively to larger areas would ordinarily result in overestimates as the smaller size of the plots permits runoff from a greater proportion of their total area than would occur from larger areas, particularly during small storms. The measurements of total erosion, on the other hand, if applied quantitatively to larger areas, would be conservative, for erosion-damage is a function of the volume and velocity of runoff which is limited by the area of the plots, particularly during the larger storms of long duration.

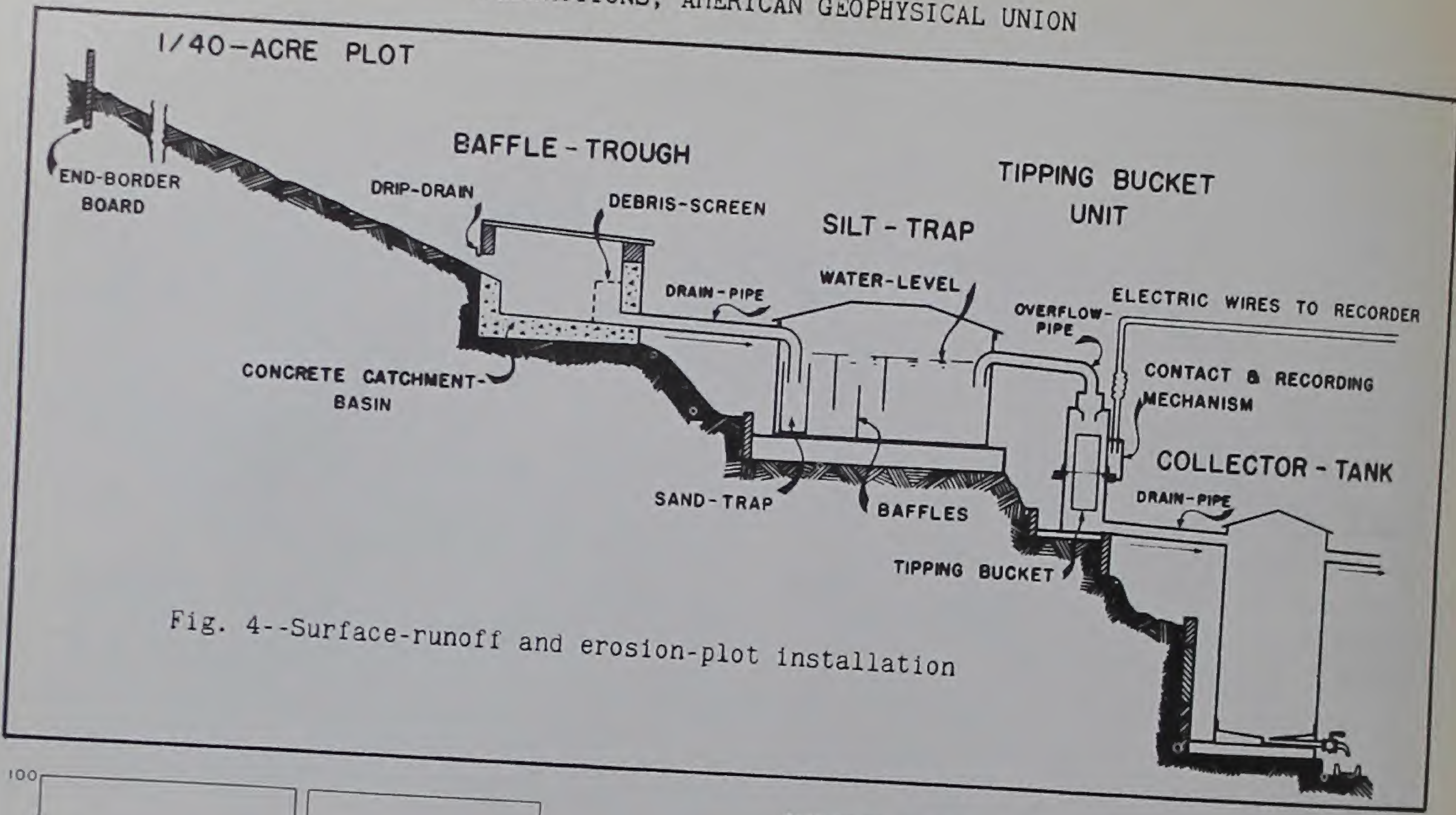


Fig. 4--Surface-runoff and erosion-plot installation

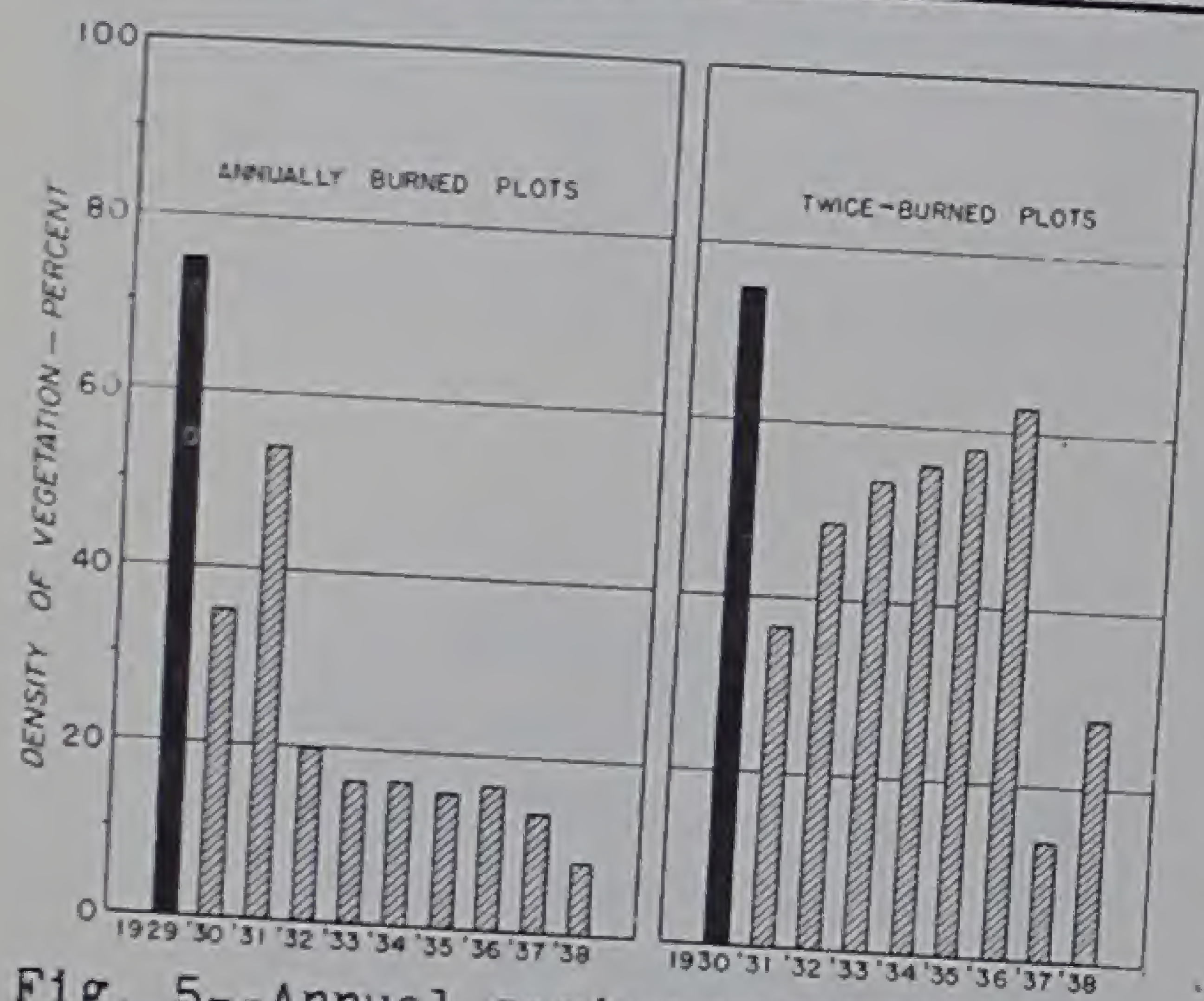


Fig. 5--Annual spring vegetation-cover on annually and periodically burned plots at North Fork, 1929-38

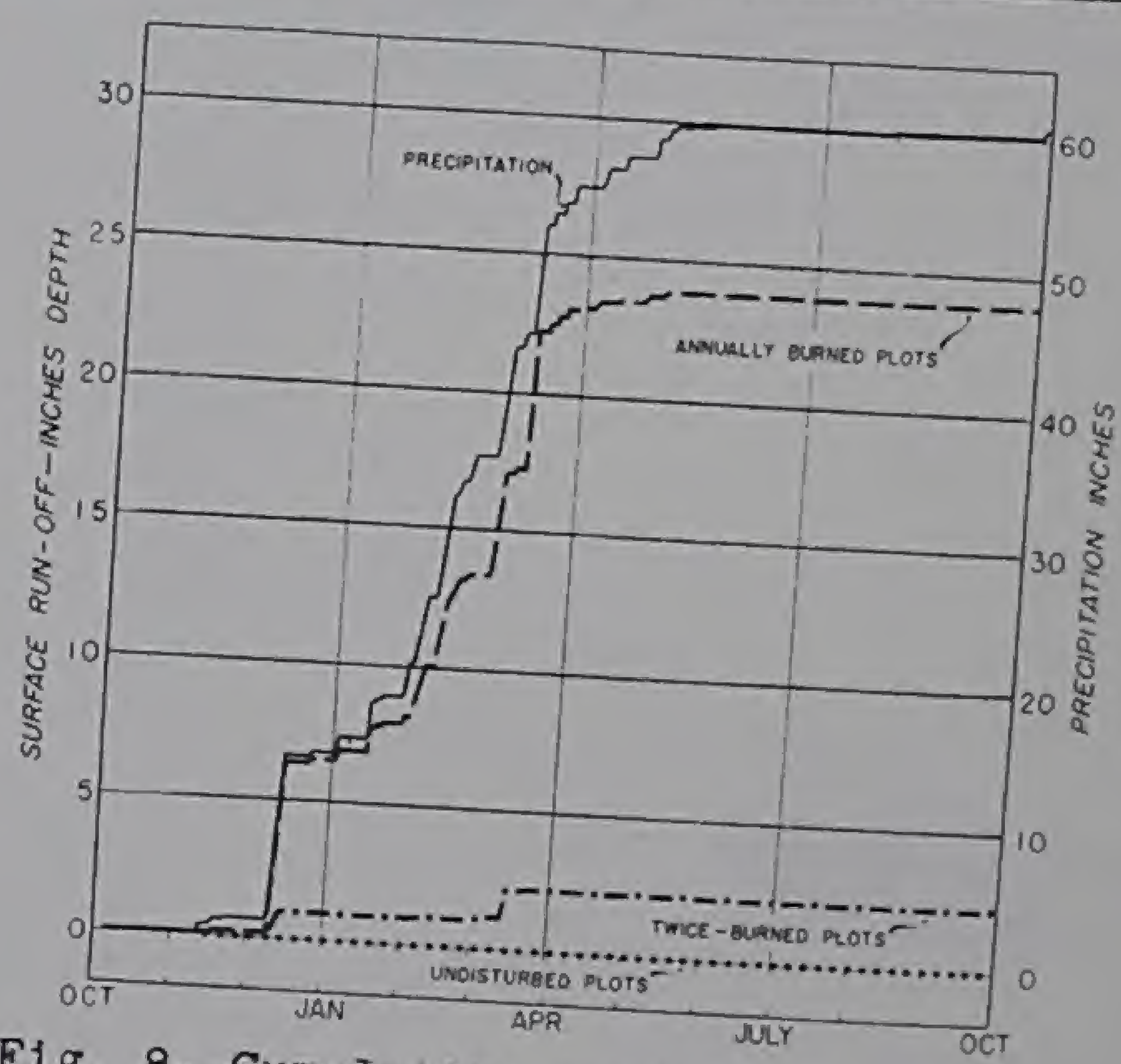


Fig. 8--Cumulative surface-runoff from North Fork 1/40-acre plots for season October 1, 1937, to September 30, 1938.

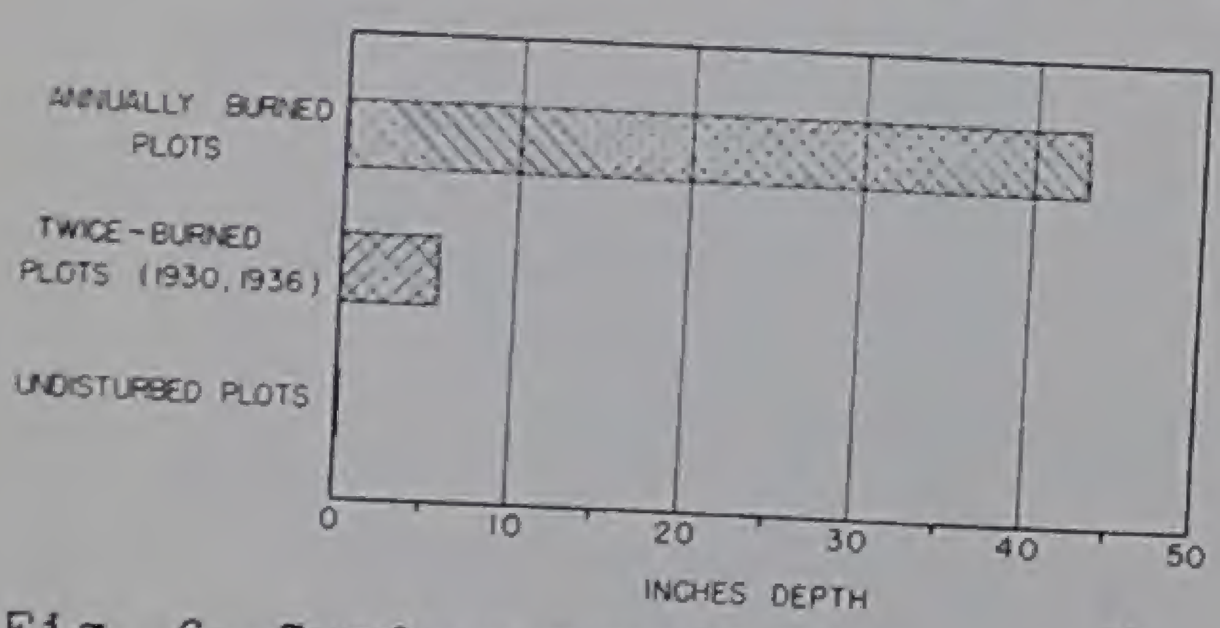


Fig. 6--Surface-runoff from 1/40-acre plots at North Fork, 1929-38

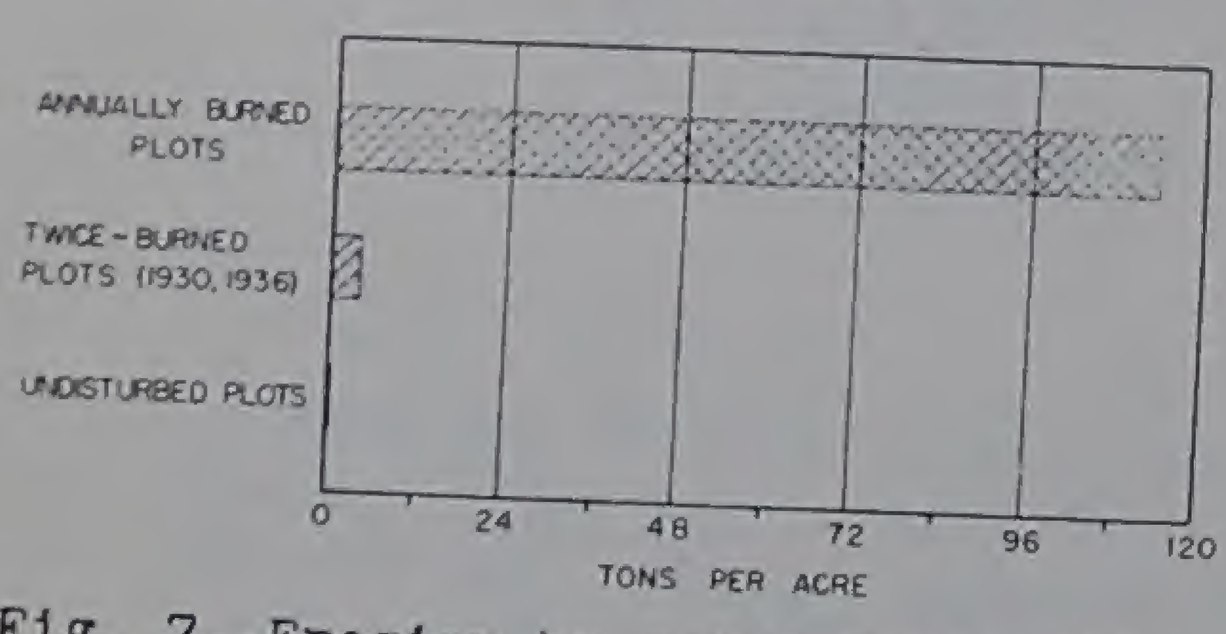


Fig. 7--Erosion by water from 1/40-acre plots at North Fork, 1929-38 (More than 0.8 inch of surface-soil has been washed from the annually burned plots since 1929)

A total of nearly 42.9 inches of surface-runoff, the equivalent of more than 14 per cent of the total precipitation, was recorded from the annually burned plots during the nine-year period of the experiment (Fig. 6), while from the twice-burned plots a total of 5.64 inches of surface-runoff, equivalent to nearly two per cent of the precipitation, was recorded. The greater proportion, or approximately 88 per cent, of the runoff from the twice-burned plots occurred during the first two seasons following each of the burnings.

The runoff from the annually burned plots washed away the surface-soil at a rate of more than 113 tons per acre and from the twice-burned plots at a rate of more than four tons per acre (Fig. 7). In contrast to the comparatively high runoff- and erosion-rates from the annually and the twice-burned plots, the runoff from the undisturbed plots has never exceeded 0.1 per cent of the annual precipitation and has never reached sufficient volume to produce a measurable amount of water-erosion.

Compared with the results of individual seasons and storms of high rainfall-intensities, the proportions of total runoff and erosion for the nine-year period are conservative, for the period contains many seasons and storms with low rain-intensities or with the precipitation occurring

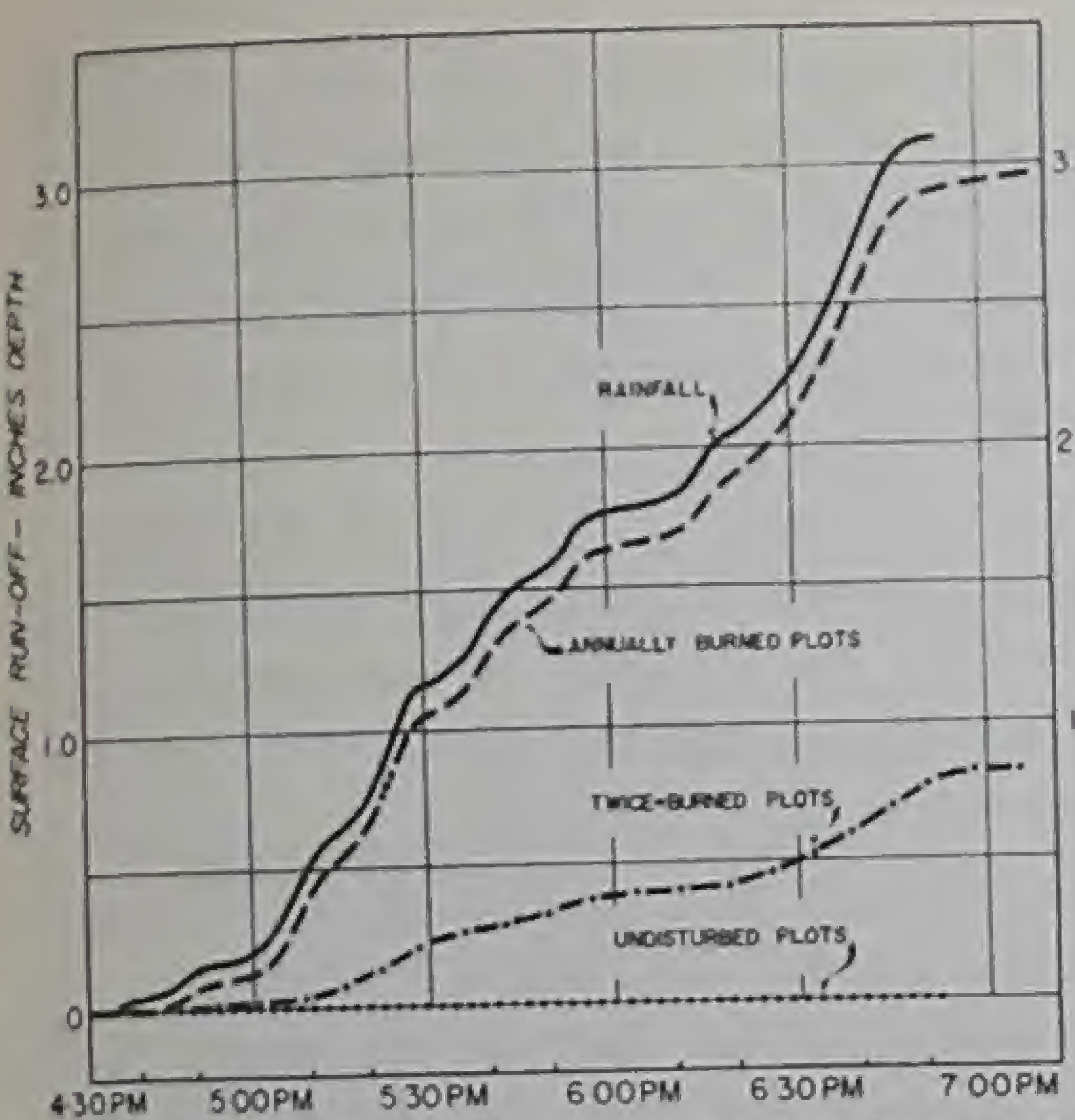


Fig. 10--Cumulative runoff from North Fork 1/40-acre plots for one phase of storm of March 11, 1938

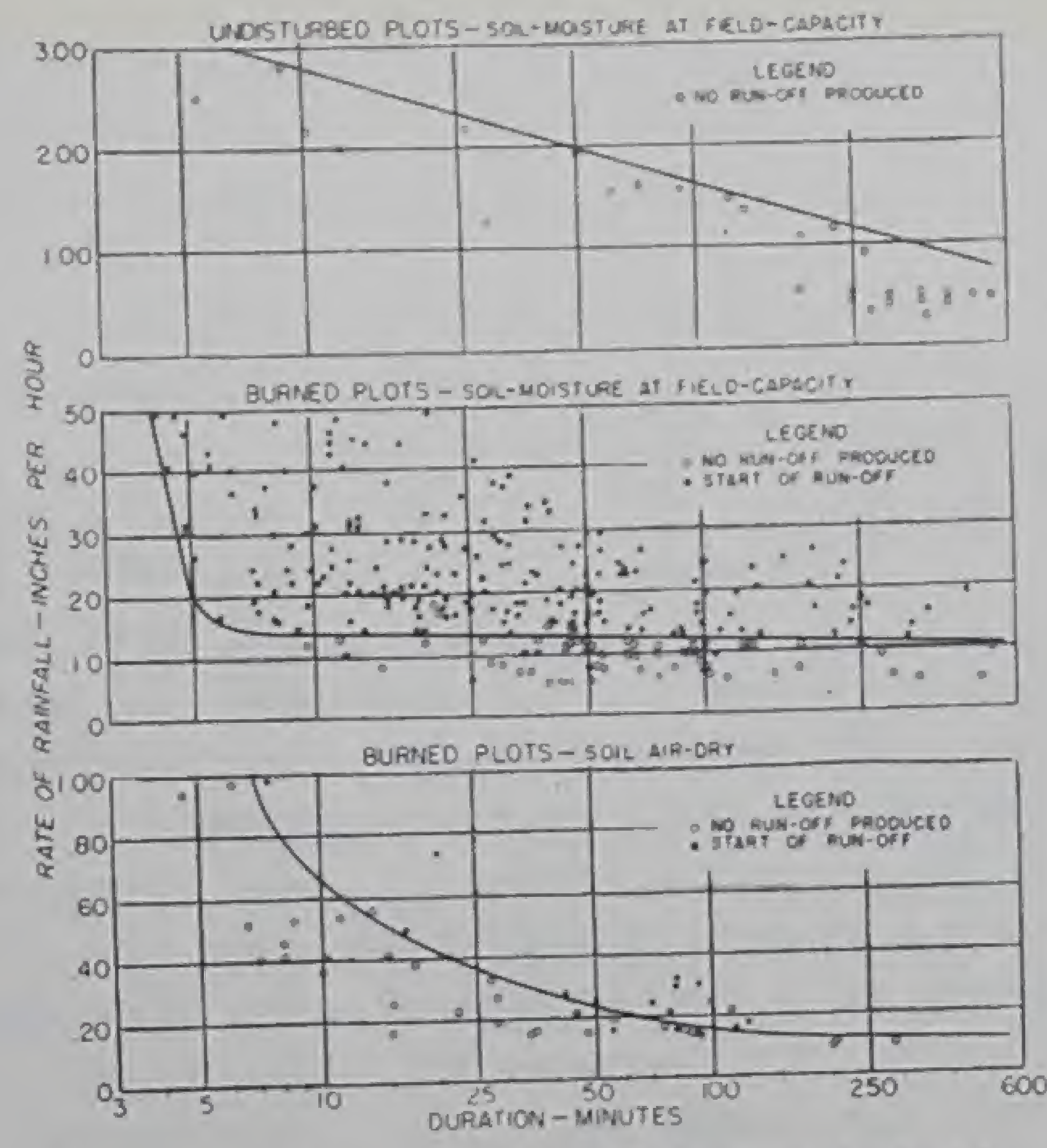


Fig. 9--Time required for rainfall of varying intensities to produce runoff on undisturbed and annually burned 1/40-acre plots at North Fork

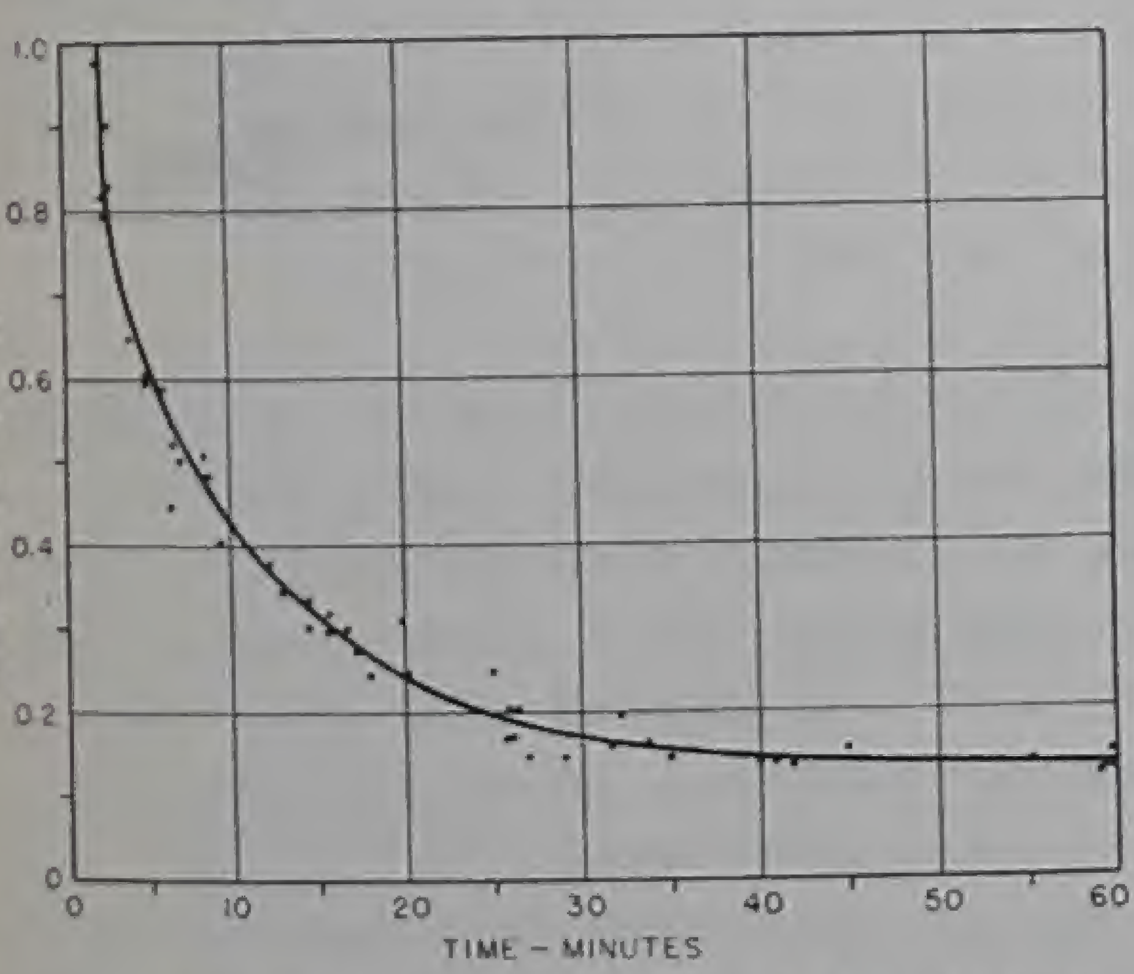


Fig. 11--Influence of rainfall-intensity upon time required for surface-runoff to obtain a constant rate of flow from annually burned plots at North Fork, 1934-38 (Soil-moisture content at beginning of runoff was at or near field-capacity

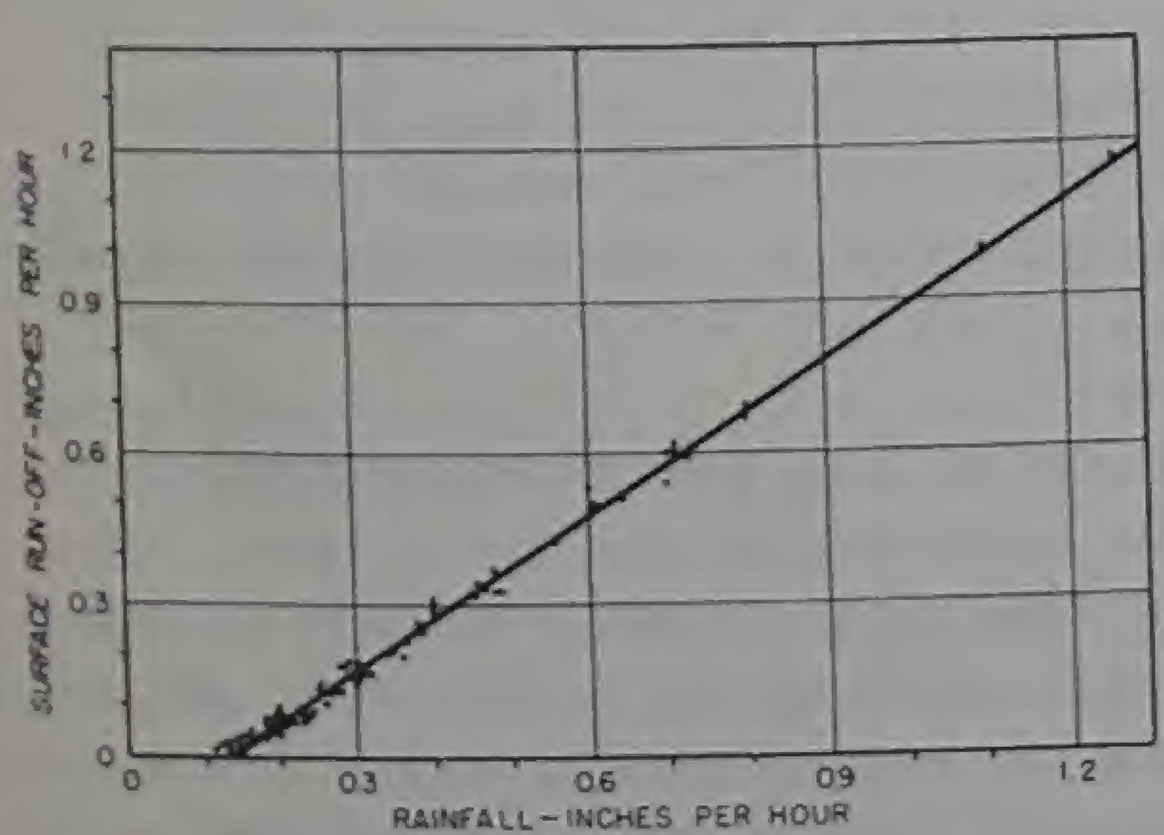


Fig. 12--Relation between rain-intensity and surface-runoff from annually burned plots at North Fork, 1934-38 (Soil-moisture content at beginning of runoff was at or near field-capacity)

largely as snow. For example, during the 1937-38 season (Fig. 8), when the total precipitation was 60.77 inches and there were many storms of high-intensity rainfall, the surface-runoff from the annually burned plots was 23.8 inches, or over 39 per cent of the precipitation; the runoff from the twice-burned plots having a two-year regrowth of vegetation was 2.2 inches, or about 3.6 per cent of the precipitation; and the runoff from the undisturbed plots was less than 0.01 inch, or only a trace of the precipitation. This runoff caused soil-erosion at a rate exceeding 80 tons per acre from the annually burned plots and at a rate of over 0.4 ton per acre from the twice-burned plots. In certain storms with high rainfall-intensities during this season the runoff-rates from the annually burned plots often exceeded 50 per cent of the precipitation.

Some rainfall-, runoff-, and infiltration-relations on the annually burned plots

Changes in the environmental factors, brought about by burning the vegetation, have resulted in a reduction of 90 to 95 per cent in the infiltration-capacity of the soil on the 1/40-acre annually burned plots. This reduction in the infiltration-capacity of the soil was caused largely by (1) an almost total destruction of the litter-cover, (2) a reduction of 70 to 75 per cent in the organic matter of the surface-soil, (3) a reduction of 70 to 80 per cent in the activities of certain of the soil-fauna, such as earthworms and burrowing insects, and (4) the plugging of the soil-pores and the destruction of the surface-soil structure caused by direct exposure to weather, surface-runoff, and erosion.

The decrease in the infiltration-capacity of the soil and the reduction of the mechanical obstructions to surface-flow resulting from burning the vegetation have greatly lowered the intensity and duration of precipitation required to produce surface-runoff from the burned plots. The boundary-line curves in Figure 9 show the intensities and durations of rainfall which produced or failed to produce runoff from the plots under different soil-moisture conditions during the last five years of the experiment. The center boundary-line shows that when the soil-moisture is at or near field-capacity rainfall-rates as low as from 0.1 to 0.14 inch per hour lasting for periods of six minutes or more will produce runoff from the annually burned plots, indicating an average

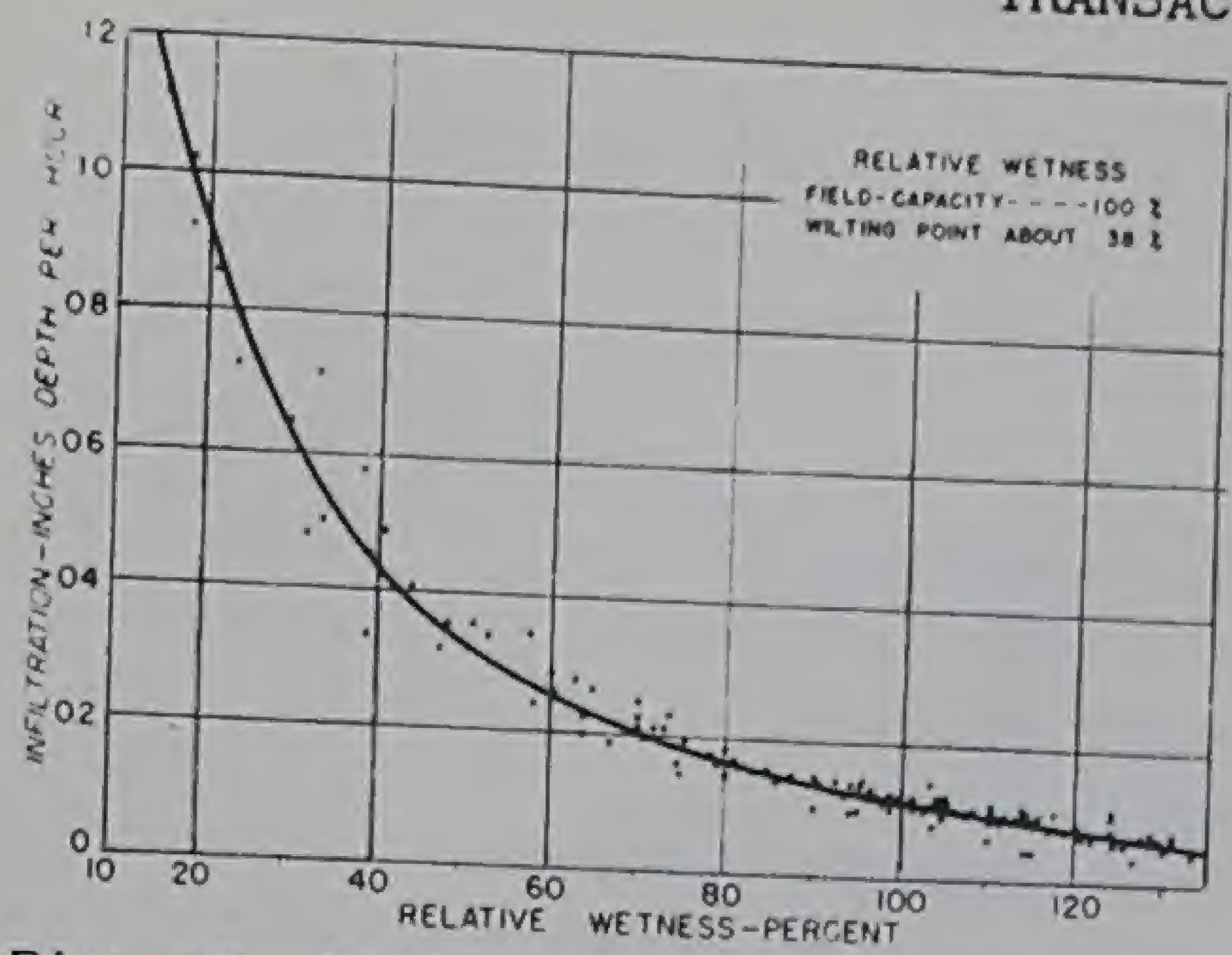


Fig. 13--Influence of moisture on infiltration-capacity of soil on annually burned plots at North Fork (Relative wetness is moisture-content of soil expressed as a percentage of its field-capacity; the percentages of moisture used are based on moisture-content of soil at start of storm or phase of storm during which observations were made)

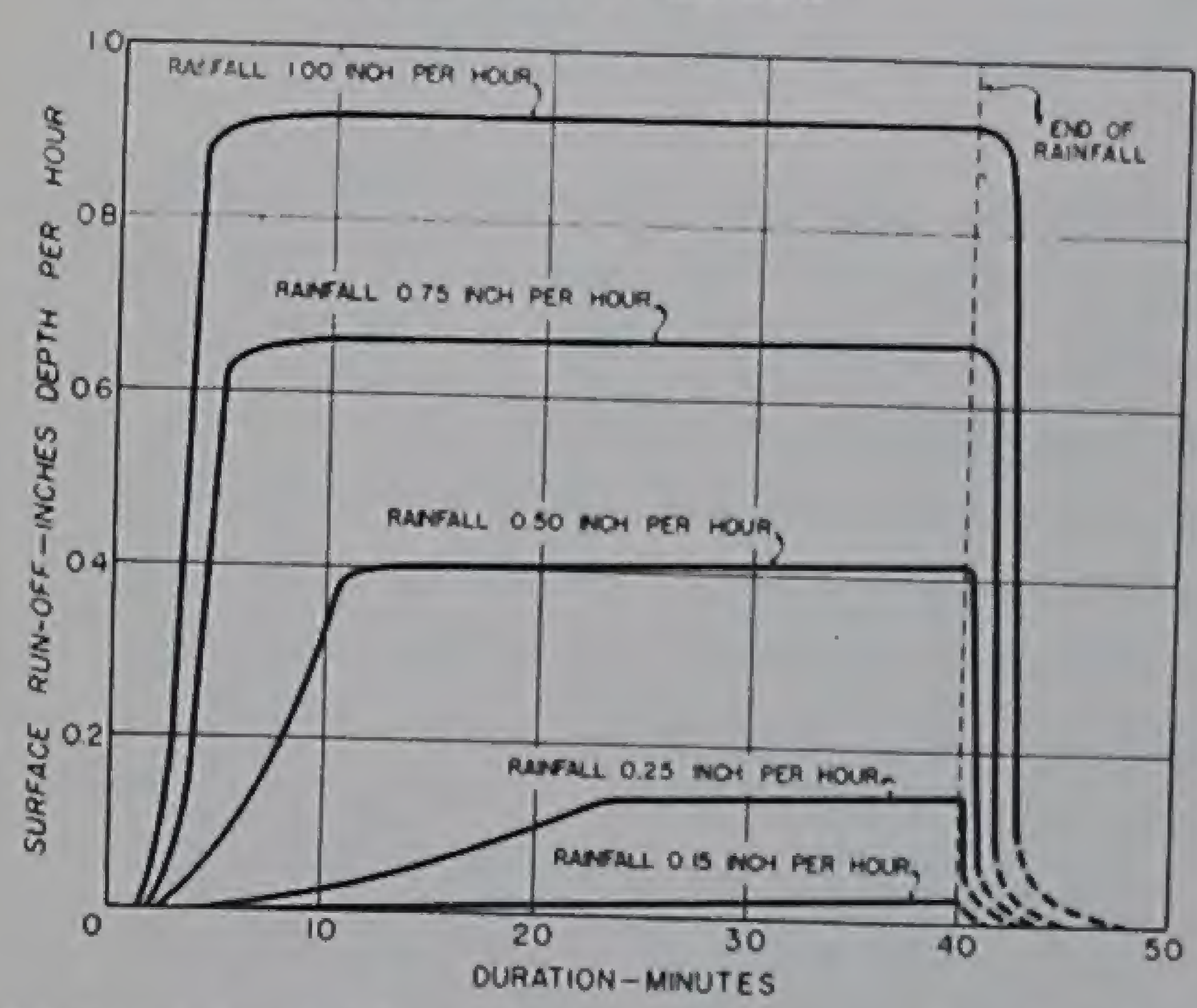


Fig. 14--Effect of different rainfall-intensities upon surface-runoff and infiltration-rates

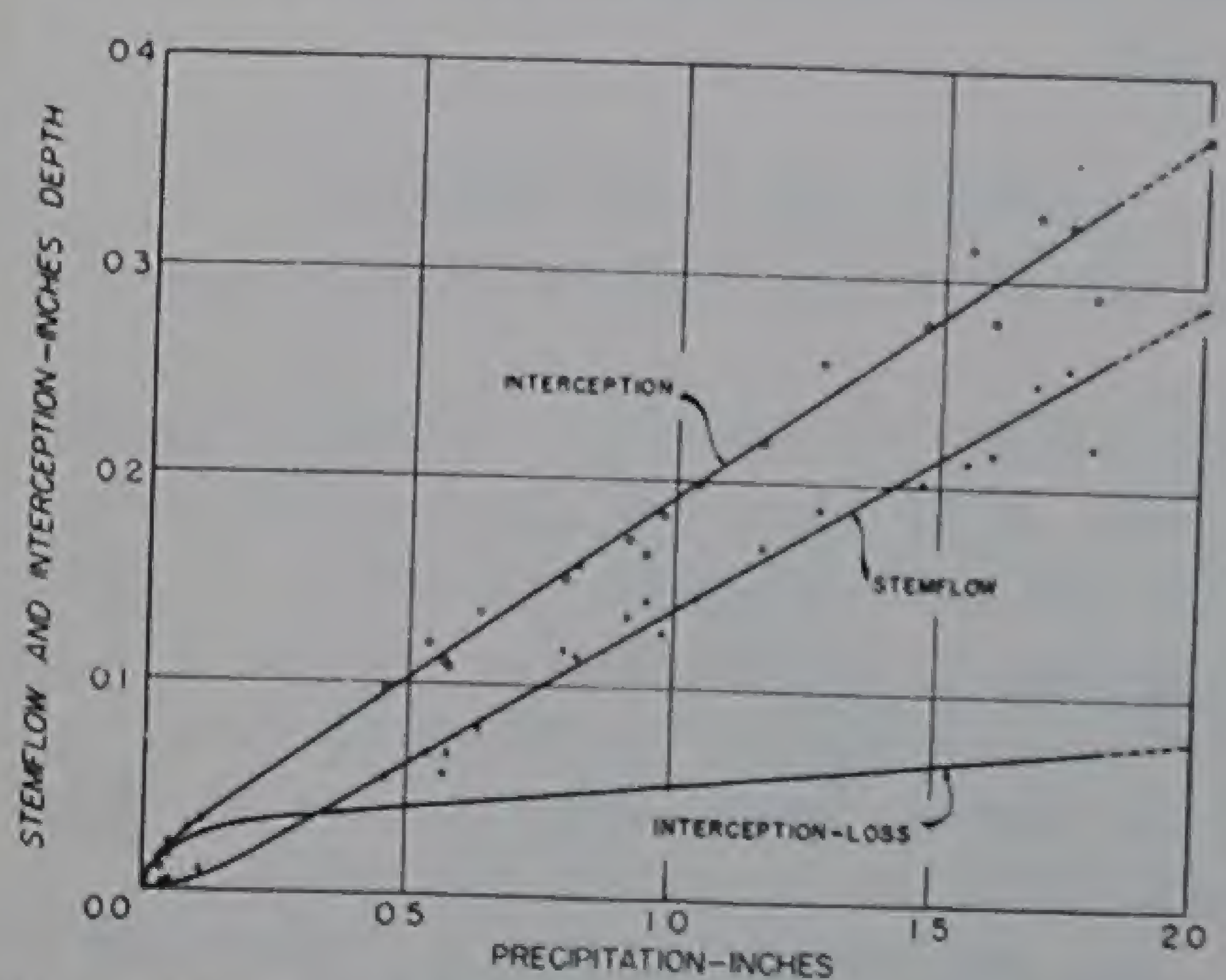


Fig. 15--Relations between total interception, stemflow, and amount of precipitation-loss by direct evaporation from vegetation of undisturbed plots during winter rainstorms, December 1, 1937, to March 20, 1938 (Storms with precipitation in form of snow, or those occurring during periods when a greater proportion of vegetation was in foliage, showed largest evaporation-losses)

infiltration-capacity of approximately 0.12 inch per hour. The downward trend of the boundary-line during the first six minutes of rainfall is largely due to such factors as interception, depression-storage, and instrumentation-lag and does not necessarily indicate a higher infiltration-capacity during this period.

The upper boundary-line shows that under similar soil-moisture conditions a rainfall in excess of three inches per hour for periods as long as seven minutes or a rainfall of two inches per hour for at least 50 minutes would be necessary to produce runoff on the undisturbed plots. Because the lack of rainfall of sufficient intensities and durations to produce runoff from the undisturbed plots does not permit the establishment of the upper limits of the boundary-line, the actual infiltration-capacity of these plots is undoubtedly much higher than the minimum indicated. In fact, infiltration-tests made on these plots employing the North Fork infiltrometer indicated infiltration-capacities in excess of 7.5 inches per hour under summer dry-soil conditions and over 3.5 inches per hour with the soil-moisture at or near field-capacity.

The lower boundary-line in Figure 9 shows that when the soil-moisture on the annually burned plots at the start of a storm is near or below the wilting-point, a very much longer time is required for a given rainfall to produce runoff than when the soil-moisture is at field-capacity. However, when the rainfall is of sufficiently low intensity and long-enough duration to permit the gradual wetting of the surface-soil before the start of runoff the initial soil-moisture has much less effect on the time required to produce runoff than when the rainfall is of higher intensities.

These differences in the infiltration-capacities of the soils of the undisturbed and the annually burned plots help to explain the large differences in surface-runoff. For example, during the last five years of the experiment over 50 per cent of the rainfall fell at intensities exceeding the infiltration-capacity of the soil of the annually burned plots, whereas less than one per cent exceeded the infiltration-capacity of the soil on the undisturbed plots.

Figure 10, showing one of the record-storms experienced during the study, illustrates the influence of the infiltration-capacity of the soil on the rainfall-runoff relations. In one phase of this storm 3.10 inches of rain fell during a period of approximately 2-1/3 hours, an average rate of over 1.33 inches per hour. During short intervals the rainfall-rate often exceeded three inches per hour and at one time reached a rate of seven inches per hour. From the annually burned plots, with

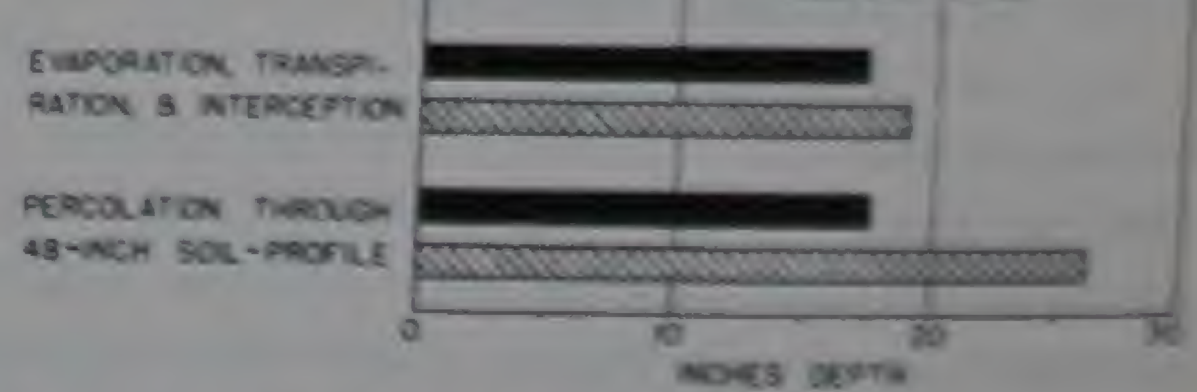


Fig. 16--Seasonal variations in moisture-content of soil-profiles of annually burned and undisturbed plots at North Fork, 1937-38

only a sparse growth of volunteer vegetation, approximately 96 per cent of the rainfall ran off. From the twice-burned plots, which at the time of this storm had a two-year regrowth of vegetation, over 28 per cent of the rainfall ran off. In contrast, from the unburned plots, with the natural cover intact, no surface-runoff occurred.

Erosion was not measured separately for this phase of the storm, but field-observations showed the rate to be well in excess of 18 tons per acre from the annually burned plots, about 0.2 ton per acre from the twice-burned plots, and nothing from the undisturbed plots.

The relation between different rainfall-intensities and time required to produce constant runoff-rates from the annually burned plots during periods when soil-moisture was at field-capacity at the start of runoff is shown in Figure 11. A rainfall of 0.15 inch per hour would require, after the start of runoff, approximately 37 minutes to produce a constant flow. As the plots are 108.9 feet in length, this would indicate an average surface-flow velocity of about 2.9 feet per minute during this initial period of runoff. For rainfall of higher intensities the length of plot becomes a limiting factor much sooner, and the velocities of flow are greater. For example, in a rainfall of 0.4 inch per hour the average velocity of surface-flow would be approximately 9.8 feet per minute and for a rainfall of one inch per hour about 43.0 feet per minute. Rainfall creating these high volumes and velocities of surface-runoff contributed most to the erosion-losses of the plots. Little or no measurable erosion has been caused by storms with surface-flow velocities of under five feet per minute.

During the first three or four seasons after annual burning of the vegetation was begun there was a comparatively rapid decrease in the infiltration-capacity of the soil on the annually burned plots. This decrease in infiltration-capacity was largely caused by puddling, plugging of the soil-pores by erosion, and other changes in the physical properties of the surface-soil resulting from its direct exposure to the effects of climate, particularly the beating effects of high-intensity rainfall. By the fourth season the structure of the surface-soil appeared to have become more or less stabilized. Differences in the character and intensity of rainfall during subsequent seasons appeared to have little or no direct influence on infiltration-capacity, except as these differences influenced soil-moisture or as the rainfall contributed to a continued, but very gradual, reduction in infiltration-capacity perceptible only over long periods of time. This is illustrated by Figure 12, which shows that when the soil-moisture of the annually burned plots is at field-capacity there is, within the limits of the data, a straight-line relationship between rates of rainfall and rates of surface-runoff. [The runoff-rates used in Figures 12 and 13 and in the subsequent discussion are the runoff-rates observed at the time when length of plot becomes a limiting factor (Fig. 11).] The difference between the rate of rainfall and the rate of surface-runoff at any point along the curve is a measure of infiltration-capacity which, for these data, is a constant of 0.12 inch per hour.

As indicated in the foregoing discussion, the influence of soil-moisture on infiltration, surface-runoff, and erosion establishes soil-moisture as an important factor in the hydrologic cycle. The curve in Figure 13 illustrates the effect of moisture-content on the infiltration-capacity of the soil on the annually burned plots under conditions of natural rainfall, as observed during the last five-year period of the study. Although the infiltration-capacity of the soil on the annually burned plots appears to be comparatively constant for given moisture-conditions it varies greatly with changes in soil-moisture. When, at the start of rainfall, the moisture-content of the upper 12-inch depth of soil was below the wilting-point, the infiltration-rates have exceeded an inch per hour for periods of several minutes. With increases in moisture the infiltration-capacity of the soil decreases rapidly until a moisture-content approximately midway between the wilting-point and field-capacity has been reached. From this point to complete saturation of the soil the infiltration-capacity continues to decrease with increases in its moisture-content, but the rate of decrease is more gradual.

The combined influence of soil-moisture and volume, intensity, and duration of rainfall on surface-runoff from the annually burned plots is shown in Figure 14. These curves or surface-runoff hydrographs do not represent actual storms but are built up from the data used in Figures 9, 11, 12, and 13, and from runoff- and rainfall-rates observed during the last five years of the experiment. As would be expected, rainfall occurring at the higher rates requires a shorter time to satisfy the requirements of such factors as instrumentation-lag, initial interception, and depression-storage and to produce and to establish constant rates of surface-runoff than rainfall of lower rates. After the break in the runoff-curve, which occurs when the size of plot becomes a limiting factor, there is a gradual but continual decrease in the infiltration-capacity as the soil approaches saturation. The higher the rainfall-intensities the lower the infiltration-rate obtained in a given unit of time. By carrying the analyses of the surface-runoff hydrographs further, estimates of depression-storage, initial detention, and velocity of

flow can be obtained. [See P. B. Rowe, The construction, operation, and use of the North Fork infiltrometer, U. S. Dept. Agric., Tech. Bull., Flood Control Coordinating Committee, Calif. Forest and Range Exp. Sta., Misc. Publ. No. 1 (February 1940).]

Some relations between precipitation and surface-runoff, interception, transpiration, and evaporation

On every land-area a large part of the precipitation is annually returned to the atmosphere by various processes of evaporation, such as evaporation of precipitation intercepted by the vegetation, transpiration, and direct evaporation from the soil-surface. In measuring these losses at North Fork, interception and soil-moisture sampling-studies were employed to supplement the results of the surface-runoff plot and lysimeter experiments.

The total interception of precipitation, stemflow, and interception-losses on the undisturbed runoff-plots for a typical rainy season are shown in Figure 15. The total interception was equivalent to approximately 20 per cent of the precipitation. However, over 75 per cent of the intercepted precipitation, or the equivalent of approximately 15 per cent of the total precipitation, in the end reached the soil as flow along the stems of the shrub- and tree-vegetation. The interception-loss by direct evaporation from the vegetation was, therefore, very small, averaging only about five per cent of the total precipitation.

The influence of vegetation on the soil-evaporation losses (evaporation and transpiration) was determined by special soil-moisture sampling and by supplementary lysimeter experiments. The soil-moisture samples were collected from undisturbed vegetation, annually burned and completely denuded areas situated in or adjacent to the runoff-plots representing like conditions of cover. During periods of active percolation the sampling procedures were manipulated so as to permit isolation and evaluation of the different processes affecting the disposition of precipitation. Precipitation occurring during periods of non-percolation when the soil-moisture was below field-capacity was considered to be either retained by the soil, lost as surface-runoff, utilized by the vegetation in growth, or returned to the atmosphere by direct evaporation.

Percolation through the upper 48-inch depth of soil for each of the conditions sampled was calculated by the following formula:

Percolation = [(Precipitation during storms within the percolation-period) – (surface-runoff + actual interception + transpiration and evaporation during periods of active percolation + the amount of precipitation required from the first storm causing percolation to bring the moisture-content of the soil to field-capacity)]

The seasonal variations in soil-moisture of the annually burned and the undisturbed areas during the season of 1937-38 are shown in Figure 16 for two soil-profiles. The upper diagram represents a 48-inch soil-profile of the areas in the undisturbed cover and the lower a similar profile of the annually burned area. The soil in the moisture-range, indicated in the legend as "2 per cent or less," has a moisture-content within two per cent or less of oven dryness and indicates a relative wetness of approximately 12 per cent or less of that at field-capacity. The boundary-line between the zones "2 per cent to wilting-point" and "wilting-point to field-capacity" indicates a relative wetness of about 38 per cent, and the boundary-line between the zones "wilting-point to field-capacity" and "field-capacity or above" indicates a relative wetness of approximately 100 per cent.

At the start of sampling each fall the total moisture-content of the soil of the undisturbed plots, particularly in the upper 18 inches, was slightly higher than that of the annually burned plots. With the fall rains the rate of wetting was more rapid on the undisturbed plots than on the burned plots. For example, in the fall of 1937 percolation on the undisturbed plots started about December 11, after about 8.5 inches of precipitation, whereas the moisture-content of the soil-profile of the annually burned plots did not reach field-capacity until about January 14, after approximately 16.5 inches of rainfall had been recorded. The difference in time and amount of precipitation required to bring the two soils to field-capacity was largely due to the differences in the infiltration-capacities of the soils, to the greater amounts of runoff from the annually burned plots, and to the differences in the surface-evaporation rates. The higher surface-evaporation losses from the burned plots were largely compensated for by the higher interception- and transpiration-losses from the undisturbed plots, the difference in percolation, therefore, being almost equal to the difference in surface-runoff.

Fluctuations in the soil-moisture during the rainy season, because of surface drying between storms, were less on the undisturbed than on the annually burned plots, and at the end of the

Table 1--Average yearly interception, evaporation, runoff, transpiration, and percolation from undisturbed and annually burned plots during periods of percolation, 1935-38[a]

Plots	Rainfall during percolation	Percolation-period	Interception	Surface-evaporation	Surface-runoff	Transpiration	Percolation
	inches	days	inches	inches	inches	inches	inches
Undisturbed	34.94	122	1.94	3.00	0.01	3.81	26.18
Annually burned	30.43	101	b	4.13	7.10	2.07	17.64

[a]Evaporation, transpiration, and percolation are for a 48-inch soil-depth.
[b]Trace only.

rainy season drying in the upper 12-inch depth of soil was more rapid and more complete on the burned areas. Drying below the 12-inch depth was more rapid on the undisturbed areas with an established vegetation-cover. However, by the end of the summer the total moisture-content below the 12-inch depth was about equal on both the annually burned and the undisturbed plots, the vegetation in both cases having utilized all the available soil-moisture.

The average annual disposition of precipitation by classes of use during the period of active percolation for the 1935-38 seasons is shown in Table 1. Daily evaporation-losses (interception, surface-evaporation, and transpiration) during the winter periods of active percolation averaged about 0.072 inch per day from the areas in the undisturbed vegetation-cover, or approximately 0.01 inch per day more than from the annually burned areas. Interception- and transpiration-losses were greater from the undisturbed areas, and surface-soil evaporation-losses were greater from the burned areas.

As shown by Figure 17, the total yearly surface-runoff from the annually burned plots during the last four years of the experiment averaged over ten inches more than from the undisturbed plots. The total yearly evaporation-losses from the undisturbed plots averaged about 19 inches, or about 1.7 inches more than from the annually burned plots, and the percolation through the 48-inch soil-profile of the undisturbed plots averaged 26.2 inches, or about 8.5 inches more than for the annually burned areas. The average annual water-yield--surface-runoff plus percolation--from the undisturbed plots was about 26.2 inches, or only about 1.7 inches less than from the annually burned plots.

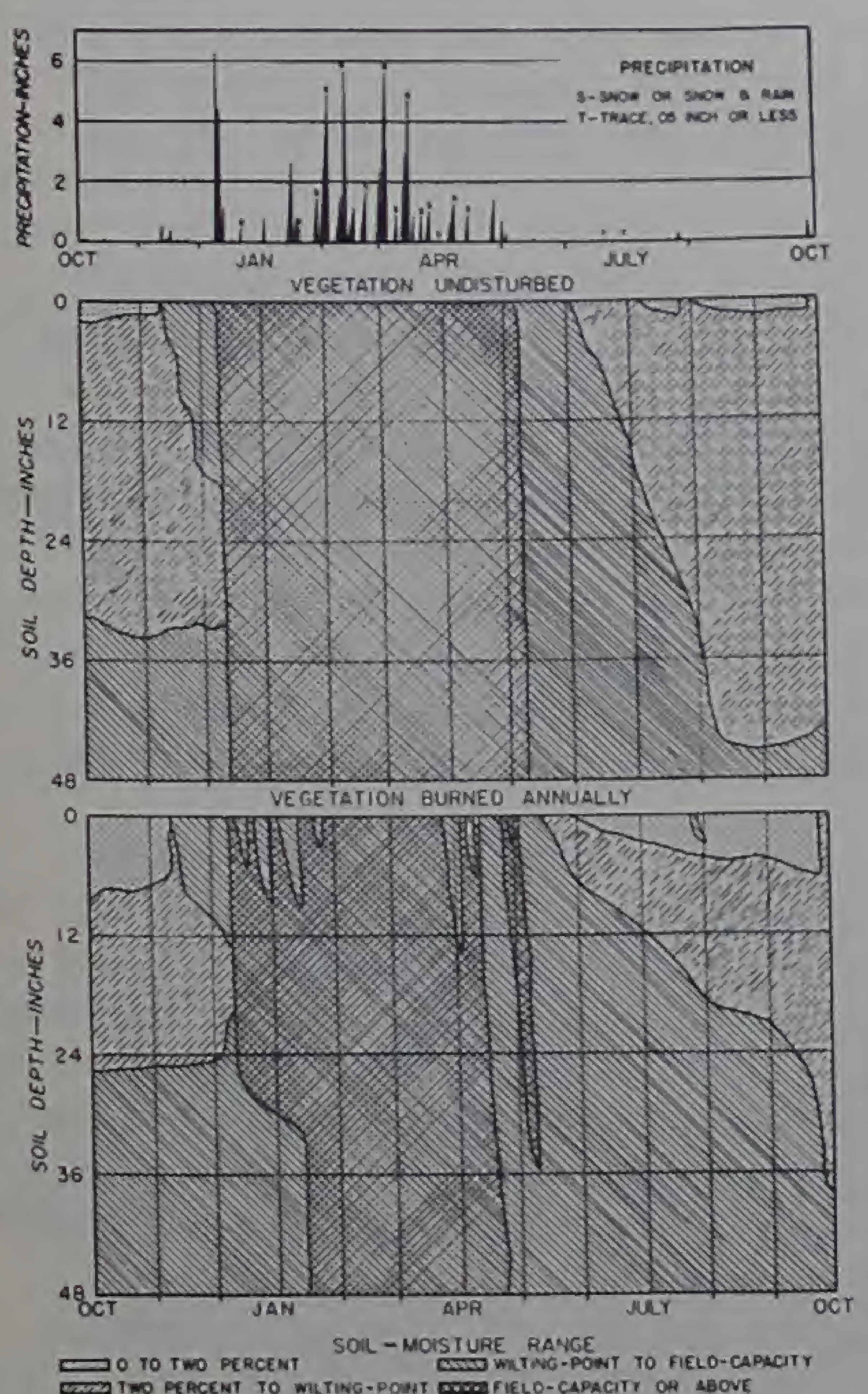


Fig. 17--Average yearly surface-runoff, interception, transpiration, evaporation, and percolation from annually burned and undisturbed plots at North Fork, 1935-38

Although the total water-yield of the annually burned and undisturbed plots was about the same the results of the lysimeter studies indicate wide differences in average daily yields. For example, the average daily total yield of water from vegetation-covered lysimeters was only about 60 per cent of the average daily yield from lysimeters containing a denuded soil. The period of water-yield of the lysimeters containing vegetation, however, was about twice as long as that of the denuded-soil lysimeters.

The most significant difference in the soil-water relations of the undisturbed vegetation and the annually burned plots was not in the total water-yield but rather in the quality and distribution of the water yielded. Approximately 37 per cent of the water-yield from the annually burned plots was surface-runoff, much of which was laden with silt and debris and thus unsuited for many uses. Furthermore, a large proportion of this runoff occurred during flood-periods when the streams of the foothills and valley were running full, and any additional water supplied to them was added to the flood-peaks and often carried to the ocean unused. On the other hand, the yield of water from the undisturbed plots occurred

largely as delayed, clear seepage through the soil resulting in a more regulated and prolonged stream-flow. This does not mean that controlled use of the land would necessarily result in increased flood- and erosion-hazards or in decreased water-production. In fact, it is conceivable that under proper management of watershed the use of the land for the production of wood and grazing might be beneficial in effecting and maintaining the maximum yield of usable water from the area. Future studies, some of which are now in progress, should serve in part to answer this problem.

Conclusions

From the results of the North Fork study it may be concluded:

(1) That (a) size of area, (b) character, intensity, and duration of precipitation, and (c) moisture-content of the soil, because of their influence on infiltration, surface-runoff, erosion, and water-yield, are important factors in the hydrology of the Sierra Nevada foothills.

(2) That the undisturbed vegetation-cover of the woodland-chaparral type, by protecting and maintaining soil-conditions favorable to the development of high infiltration-capacities, is effective in the control of surface-runoff, erosion, and floods.

(3) That a natural cover of woodland-chaparral vegetation, by decreasing surface-runoff and erosion and by serving to regulate and prolong stream-flow from the area, at little or no reduction in the quantity of water-yield, is highly beneficial in the production of usable water.

California Forest and Range Experiment Station of U. S. Department
of Agriculture and University of California,
Berkeley, California

DISCUSSION

F. J. VEIHMEYER (University of California, Davis, California)--My colleagues and I have been carrying on experiments with soils in tanks and in field-plots for a number of years with the same approach used by Mr. Rowe in his investigations. During the past six years runoff and erosion have been measured in Shasta County from plots which have been denuded by burning and from plots with undisturbed vegetation. Recently some of this work has been extended into Tehama County.

The need for replication of plots has become very evident from this work. Dependence cannot be placed upon the results from only two plots, one covered with vegetation and the other denuded. For instance, in the work mentioned, the runoff and erosion from one of the covered plots was much greater than from the adjacent bare plot and the reverse was true of another pair of plots. It would seem from Rowe's paper there were only two plots, one bare and the other covered, that is, the annually burned one and the undisturbed one.

While Mr. Lee showed that the difference between rainfall and runoff from observation for a number of years was between 12 and 13 inches, Mr. Rowe showed there was 40 inches more runoff from the annually burned plot than from the undisturbed plot which indicates much greater ground-storage than do Mr. Lee's data.

The hazard of carrying the results of plot-experiments to large areas, square miles of drainage, was pointed out by reference to a paper by W. G. Hoyt "Current technique in rainfall-runoff analysis" [Proc. Hydraulics Conference, Univ. Iowa, Studies in engineering, New Series No. 379, pp. 92-102, 1940]. Mr. Hoyt showed that in the March flood of 1938 in Southern California, during two 24-hour periods separated by less than a day, about 25 inches of rain fell on the steep slopes of the mountains tributary to the coastal plain on which the city of Los Angeles is located. Small plots showed runoff of only 0.17 inch with rainfall of about 24 inches, yet there was a serious flood. Some of the water must have gone below the soil-surface and appeared as stream-flow lower down the drainage-basin. This retardation in flow did not prevent a flood.

Mr. Rowe's data for loss of water from the soil, especially in the annually burned plot, should not be taken to be all surface-evaporation. We know that this is very small when compared with the losses from the soil by plant-transpiration. The plants which grew on the burned plot apparently depleted the soil-moisture to the same extent as did the plants on the covered plot. This substantiates a point I have emphasized many times, that on drained slopes the soil will be wet throughout at the beginning of the growing season and as dry as plants can make it at the

beginning of the next rainy season. Thus it makes little difference from a water-economy viewpoint what kind of vegetation is growing on the soil.

MR. ROWE--It is true that in the North Fork experiment only six 1/40-acre plots and four 1/100-acre plots, placed in pairs, were employed to measure differences in surface-runoff and erosion from the three conditions sampled. However, differences in runoff and erosion were so great, and with continued treatment trends were so apparent, that there was little doubt as to their significance. The smaller plots were operated for a three-year calibration-period, before the vegetation on any of them was burned, to determine inherent differences under natural conditions and to establish a basis for evaluating runoff- and erosion-results obtained after treatment was started. The soil-moisture, interception, lysimeter, infiltration, and other experiments also served to supplement results of the plot-studies in evaluating immediate and long-time effects of experimental treatments employed. Further, similar plot experiments made by the California Forest and Range Experiment Station in 12 different areas of the chaparral type throughout the State, in which 75 plots were employed and data representing over 400 plot-years were obtained, have without exception yielded results qualitatively in agreement with those obtained at North Fork.

The 43 inches more of surface-runoff (flow entirely over the surface of the soil) from the annually burned than from the undisturbed plots was the total difference for the nine-year period of the study. This difference in surface-runoff is not and should not be considered a measure of the difference in the amounts of water retained by soils of the burned and of the undisturbed plots. The total water-yield (surface-runoff plus percolation through the 48-inch depths of soil) was approximately the same for both areas. As this would indicate, there were very small differences in total water-retention by the soils (infiltration less percolation, transpiration, and evaporation) or in total evaporation-losses (interception, transpiration, and direct evaporation from the soil) from the two areas. However, quality and distribution of water-yield were definitely better from the undisturbed than from the annually burned areas.

T. B. PLAIR (Regional Forester, Soil Conservation Service, Berkeley, California)--Mr. Rowe's paper gives specific figures as to runoff-rainfall relations, disposition of precipitation, and an evaluation of these fundamental factors with which, in my opinion, we must work in developing adequate watershed-management plans. Specifically, there are two points which I would like to emphasize:

(1) The author points out that in the management of land for flood- and erosion-control and the production of usable water, it is essential to know the size, shape, soils and soil-conditions, and the general character of the watershed in addition to rainfall-distribution. These are essential basic data which we must have and which must be used in the development of plans of management for the conservative use of land, or soil, and its resources.

(2) The author also establishes the importance of good vegetative cover, if properly maintained in a favorable condition, to the prevention of soil-losses by water-erosion, the control of surface-runoff, and the regulation of the yield of usable water. In this connection, the author recognizes that various uses may not be detrimental, but the extent to which such uses as grazing and timber-cutting operations may go has not been determined. These data as presented are extremely significant and provide an adequate basis for additional investigative work, the results of which should be used in the field of land-use.

These data are needed, in my opinion, for the following reasons:

(1) The sample area in the San Joaquin Valley is only a small part of the State in which relatively similar conditions exist. These areas are not important solely from the standpoint of the acreage involved but from the standpoint of location with regard to intensity of use, and proximity to industrial and to irrigated farm-areas. Since most of these are below the boundaries of publicly owned and publicly administered lands, they are more or less the key to our erosion- and flood-control problems.

(2) These lands are predominantly in private ownership, so the owners must make, and are justified in expecting to make, some kind of use of them from which they may get an economic return. Since the water-resources of these lands are of a community or public value, then we cannot expect owners to manage their lands for the production of the maximum amount of usable water unless this management is also consistent with the immediate objectives of the owners.

REPORT OF COMMITTEE ON MEDIAN VERSUS ARITHMETICAL AVERAGE

P. E. Church (Chairman), Edward L. Wells, and H. P. Boardman

In the last session of the meetings of the Section of Hydrology of the American Geophysical Union in Seattle in June, 1940, a resolution recommending that "the expression of normals of precipitation in future hydrologic studies be defined by the median instead of the arithmetical average" was presented. It was moved, seconded, and passed that the resolution be referred to a committee appointed by Chairman J. C. Stevens, composed of P. E. Church (Chairman), Edward L. Wells, and H. P. Boardman. [See p. 1053, Trans. Amer. Geophys. Union, 1940.]

The Committee then weighed both the advantages and disadvantages of the median and the arithmetical average and in so doing numerous arguments, both favorable and unfavorable, were brought out.

Though there are numerous ways of expressing the central tendency of a series of observations, (a) arithmetical average, (b) geometric mean, (c) harmonic mean, (d) weighted arithmetical average, (e) mode, (f) median, and (g) frequency-distributions, the resolution called for a recommendation of the use of median in preference to the arithmetical average.

These disadvantages and advantages of the median versus the arithmetical average are listed and discussed below:

<u>Disadvantages of the median</u>

(1) The median, as the method of expressing the normal, is not always the figure which will be representative of the central tendency for all purposes. For certain purposes the arithmetical average is more useful.

(2) A large amount of work will be required to recompute the vast amount of data on record now available. This work would fall largely on the Weather Bureau which has amassed the greater part of the data now in use. The Weather Bureau does not have sufficient assistance to recompute this body of data at present.

(3) Comparatively few people outside the mathematical and engineering profession understand the exact meaning of the median whereas nearly everyone understands how the arithmetical average is computed. If the median was used it would be necessary to instruct those using the data as to the meaning of the median.

(4) When there is an extended number of observations, the arrangement of the data to determine the median is tedious and although no computation is necessary to determine this figure there is no machine on the market which will make the necessary arrangement. It is a simple and quick process to compute the arithmetical average because adding machines are almost universally available.

(5) The sum of the monthly medians for a year does not equal the annual median, whereas the sum of the monthly arithmetical averages equals the annual arithmetical average. The annual median would have to be computed from the annual amounts.

(6) Where more than half the figures in a series are zero, the median would convey the impression that there was a lack of a measurable quantity.

<u>Advantages of the median</u>

(1) The median, while not always the figure which will be representative of the central tendency for all purposes, is superior to the arithmetical average in many cases.

(2) The median can be determined by a simple arrangement of the series of observations and no computation is necessary. Where adding machines are not available, the determination of the average is far more tedious than the median.

(3) The median is unaffected by the abnormally large or small values of a series of observations. In the case of precipitation the abnormal values are always in excess of both the median and the arithmetical averages because of the limiting value of zero. The arithmetical average is "strongly influenced by extreme variants in a series of values."

(4) In the series of observations, if there is a <u>greatly</u> outlying value, either real or the result of an error, the median will be less affected than the arithmetical average.

(5) Negative departures of precipitation are of greater frequency than plus departures when the arithmetical average is used as the measure of the central tendency. This would not be true when the median is employed.

(6) Those who would make active use of the median as the normal are mainly hydrologists, engineers, meteorologists, etc., who would not have to be instructed as to the meaning of median. Those who do not know what the word median portrays could learn that as readily as the context of arithmetical average, normal, or mean. On published data a definition of median could be inserted.

Conclusion

The Committee recognizes the fact that the median is not superior to the arithmetical average for some certain purposes; conversely, for other uses the median is superior to the arithmetical average. It further recognizes that one figure to express the central tendency is not all inclusive. For certain phases of hydrology, the arithmetical average should and would be used, whereas for other phases the median would be much more satisfactory.

Because no one figure can represent the central tendency in a series of variants which will be the figure best adapted for all purposes, the Committee feels that it would be a step forward to have both median and arithmetical average published. To make the observations still more flexible and useful some measure of dispersion of the series of variants should also be published. Though there is the probable error, average deviation, standard deviation, and coefficient of variation, it is felt that the dispersion is best expressed by the standard deviation.

After carefully weighing the advantages and disadvantages of the median versus the arithmetical average, the Committee unanimously recommends that in the future, at least for hydrologic studies, "the expression of normals of precipitation be defined by the median."

The resolution in no way condemns or prevents the publication and use of the arithmetical average.

University of Washington,
Seattle, Washington

APPENDIX TO REPORT

H. P. Boardman

There having been no time for the discussion at the Sacramento Meeting, I do not think very many who heard the report got much of an idea of what it was all about. In spite of the fact that I signed it, I do not think it presents a very strong case for the adoption of median in place of average. It seemed, therefore, in order to prepare this brief appendix to the recommendations of the Committee.

It seems to me that we should have included a definition of median although perhaps everybody concerned knows what the term means. Taking up the points made in the Committee's report:

Under disadvantages of the median

(1) The report says, "For certain purposes the arithmetical average is more useful." The resolution specifies the use of the median only for the "expression of normals of precipitation in future hydraulic studies."

(4) It is not at all necessary to rearrange the data in order to determine the median. The method I use is to assume a trial value and then count the number of items which exceed this value; then if that is greater or less than one-half the total number of items, adopt another trial value and repeat the operation. It will not take very many trials to determine the median and I think in all cases where a large number of data are involved the time consumed would be less than that required to rearrange the items in the order of magnitude.

(6) I was at first under the impression that there was seldom, if ever, a case where there were a number of zeros in the series of numbers. However, if one were attempting to determine the normal precipitation for July or August in the Central Sierra Region over a long period of years, there would doubtless be quite a number of zeros enter into the series since we usually have very little precipitation in those months. Probably in that case the arithmetical mean would be better.

Under advantages of the median

(2) My remarks under (4) of "disadvantages" are applicable.

(3) In the second sentence the implication is that high values are the only abnormal ones; whereas in precipitation, except in the case such as I cited where there might be numerous zero-values, a value of 30 per cent of normal should be an abnormally low value and quite unusual, while there might be numerous values greater than 170 per cent of normal which shows that abnormally high values have more influence on the arithmetical average than do abnormally low values.

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THE PROCESSES RESPONSIBLE FOR THE EXTREME RATES OF PRECIPITATION

J. Bjerknes

In the absence of the author in Mexico City, an abstract was presented by J. B. Paulson, Jr.

[It is understood that Dr. Bjerknes intends to publish the complete manuscript later in bulletin form.]

University of California at Los Angeles,
Los Angeles, California

DISCUSSION

G. F. McEWEN (Scripps Institution of Oceanography, La Jolla, California) remarked on Mr. Bjerknes' paper saying that it is a rather new approach by the fundamental method to a problem that has interested engineers for a good many years; that it may prove a valuable supplementary method of the one that engineers have used based on specific methods.

E. H. BOWIE (United States Weather Bureau, San Francisco, California) spoke at some length telling of Mr. Bjerknes, who came to this country in 1939 to attend the meeting of the International Union of Geodesy and Geophysics and was unable to go back to his country and he is now a man without a country. He has been having passport difficulties and is at present in Mexico City giving a course of lectures and will return shortly with his passport in good shape. Mr. Bjerknes had made investigations in rainfall-intensities and has been working for Scripps Institution at La Jolla and this paper has been done in conjunction with the work he had done there. He is perhaps the leading meteorologist and those who know him like him and appreciate his work. Major Bowie also told of the visit of Mr. Bjerknes' father in August, 1925, and of the visit to the Cliff House to show him the Pacific Ocean. Although Dr. Bjerknes, Sr., was the world's leading oceanographer, he had never before seen the Pacific Ocean and was very much impressed by the 8,000 miles of water between San Francisco and the other side of the world.

M. P. O'BRIEN (Department of Mechanical Engineering, University of California, Berkeley, California)--Professor Bjerknes' paper is an important contribution towards a logical and reliable method of forecasting maximum rainfall in mountainous regions. Bridge engineers determine stresses caused by assumed locomotive loadings and it appears not impossible that maximum storms characteristic of each region will similarly be treated by imagining the storm to move across the drainage-basin under investigation. The elements of this solution are (1) the flow-lines characteristic of the topography and direction of air-flow, (2) the characteristics of the air-mass including temperature and moisture-content, (3) the assumption of thermydynamics equilibrium and resulting condensation, and (4) the dynamics of rain-drops. When broken down into these elements, the problem is greatly simplified and more rigorous analysis will be forthcoming as knowledge of the method spreads.

Professor Bjerknes' paper has a bearing on the question asked by Mr. Hall relative to the effect of a narrow canyon. The general trend of the topography and not small irregularities, such as narrow canyons, guides the air-currents and produces orographic rainfall. One would expect about the same rainfall in a canyon as on the heights directly above except for local shielding effects.

It is to be hoped that Professor Bjerknes can be induced to develop this method further at future meetings.

J. B. PAULSON (United States Engineers Office, Sacramento, California)--Commenting on Mr. Lee's paper and the part about the maximum precipitation at elevation 4,200 feet: We are carrying on investigations on the Pit River with stations located at 3,000 and 5,400 feet. Last year the station at 5,400 feet showed double the precipitation at 3,000 feet, while your chart showed maximum precipitation at 4,200 feet. Why should precipitation further up the slope decrease?

MR. LEE--That, of course, goes into the theory that was discussed in Professor Bjerknes' paper. It has been stated that the explanation for the decrease is the release of the latent heat by condensation at certain elevations. Why the rate should be different in different locations other than change of latitude, I am not prepared to state. In studies I have made in the southern California ranges it is about 6,000 feet, whereas along the Central Sierras it is

around 4,200 feet. If you are finding as high as 5,400 feet in Shasta, it is something else besides latitude.

MR. PAULSON--This is based on a few samples and does not prove a great deal, but the gage at 5,400 feet is greater than at 4,400 feet.

MR. LEE--Of course, you might get a different result in another period of time. It might ultimately prove to agree with the conditions throughout Central California. Time will tell.

SESSION, MORNING OF JANUARY 17, 1941--MEMORIAL AUDITORIUM
CHAIRMAN, ALBERT GIVAN

POTENTIAL FLOODS IN THE SACRAMENTO VALLEY

Walter J. Parsons, Jr.

Introduction--The planning and design of flood-control works on the tributaries and main stem of the Sacramento River inevitably requires the careful estimation and study not only of the floods of record and history but also of potential floods at various points in the river-system. Such a study is now under way and this paper will describe some of the steps in that study that are of general interest.

General physical and hydrological characteristics--The Sacramento and San Joaquin rivers drain the Great Valley of California and the mountain slopes that surround it. This Valley lies generally north and south between the continuous barrier of the Sierra Nevada and the Pacific Ocean, being separated from the ocean, however, by the comparatively low coast ranges. The prevailing winds are from the west, with marine air flowing eastward over the coast ranges and the Valley and against the great barrier of the Sierra Nevada. During the summer dry season this air is extremely stable and practically no precipitation occurs. During the wet winter season, unstable storms pass across the area causing snowfall on the high slopes of the Sierra Nevada and heavy rainfall over the coast ranges, the valley-floor, and lower slopes of the Sierra Nevada. The snow in the high country accumulates during the winter into a snow-pack as much as 30 feet in depth. When this snow-pack melts in the summer, it produces prolonged snow-melt floods of moderate height but large volume on all rivers draining the high country. The wide-spread storm-rains cause short sharp floods on rivers draining the lower mountain slopes below the snow-line. Occasionally, the storm-air is so warm that there is rain instead of snow as high as the 10,000-foot level and major floods may result on the rivers whose drainage-areas extend up into the high country. The annual precipitation during the wet season increases from 10 to 15 inches in the Valley to 55 to 60 inches at the 5,000-foot level on the Sierra slopes. Above this level, the annual precipitation slowly decreases to 40 inches at the crest of the Range. There is also a 50-inch zone of precipitation along the seaward face of the coast ranges but this is quite narrow and the landward slopes, draining into the Great Valley, receive little more rainfall than the valley-floor.

More than half of the normal annual precipitation sometimes falls in a single winter storm lasting less than a week. The distribution of the storm-precipitation is best illustrated by an isohyetal map of the great March 1907 storm that caused severe floods from end to end of the Valley. When such a storm occurs at a time when the surface is wet from previous moderate rains and the deep absorbent snow-pack does not blanket too much of the mountain slopes, general floods occur. The floods of 1907 are illustrative of this type. In December, 1937, a major storm occurred at a time when, although the ground was only moderately wet, it was bare of snow up to unusually high levels and the resulting floods set records on many streams. In contrast, the storm of December, 1929, was equal to or greater than these storms over the northern half of the Valley but, since the surface was extremely dry, only minor floods resulted. The storm of March, 1938, was also severe but such a large proportion of the mountain slopes was covered with deep snow that only minor floods occurred on the main rivers. It is evident that major winter floods require (1) a major storm, (2) a wet surface, and (3) the absence rather than the presence of a deep snow-cover over the mountain slope. The chance combination of these three factors has governed the magnitude of our historical floods.

Flood-records--Let us first discuss the available record of historical floods since they represent nature's integration of all the flood-factors. Continuous runoff-records on the main rivers of the Valley started in the period from 1895 to 1900 and have been maintained to date with increasing accuracy. Prior to this period, little exact flood-data are available but there are estimates and descriptions of occasional outstanding floods such as those of 1862 and 1867. Figure 1 shows a comparison of the maximum peak-runoff per square mile observed on rivers draining the eastern or Sierra Nevada side of the Valley. The peak-rate of runoff in cfs per square mile is plotted against total drainage-area in square miles on logarithmic paper. The runoff ranges from 120 csm for areas of 1,000 square miles to 180 csm for areas of 100 square miles. This very moderate increase in unit-rate of runoff as the drainage-area decreases is probably accounted for by the fact that the flood-producing storms are all general storms, covering the

entire mountain slope and deluging big and little streams alike, rather than local storms whose intense center can cover only a part of a large stream's drainage-area. When a particular stream has failed to produce the normal peak, this line of investigation will show that fact but will give little definite help toward solving the larger problem of potential floods.

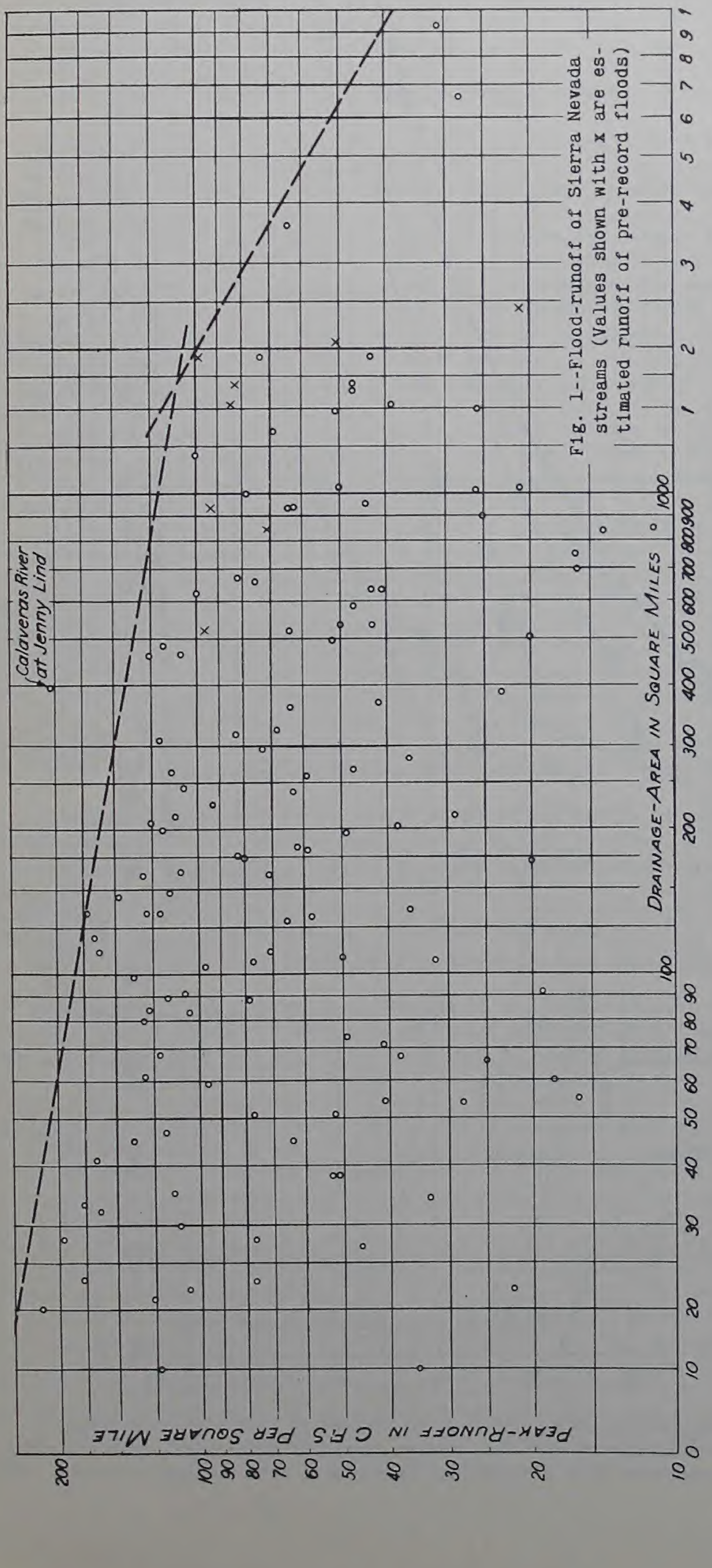

Fig. 1--Flood-runoff of Sierra Nevada streams (Values shown with x are estimated runoff of pre-record floods)

Even a cursory frequency study makes apparent how inadequate a 40-year sample is for an estimate of potential floods by frequency methods. The trend shown by the numerous small floods is suddenly broken by the occurrence of a few major floods many times greater than the largest small flood. Furthermore, since floods are caused by general storms that cover all the main rivers, the same disturbing big items occur in each record. This condition prevents the addition of several short records into one long synthetic record, a device commonly used in regions where local storms make trouble. There is also a considerable body of data indicating that the climate has swung violently back and forth in a series of cycle-like swings even during the short historical period. This data destroys faith in the record as a representative sample yet is too weak to permit quantitative adjustment of the 40-year record into the long-term mean. Direct use of the flood-record must be supplemented by a study of the separate flood-factors. When this separation is undertaken, it is apparent that in floods, as in most other complex natural events, the individual factors vary within closer limits than the floods themselves and the limits can be more reliably estimated.

Great storms--Let us discuss the potential rainfall in great storms. The 20 to 35 inches of rain of a great storm does not occur as a continuous steady fall over the duration of the storms but is concen-

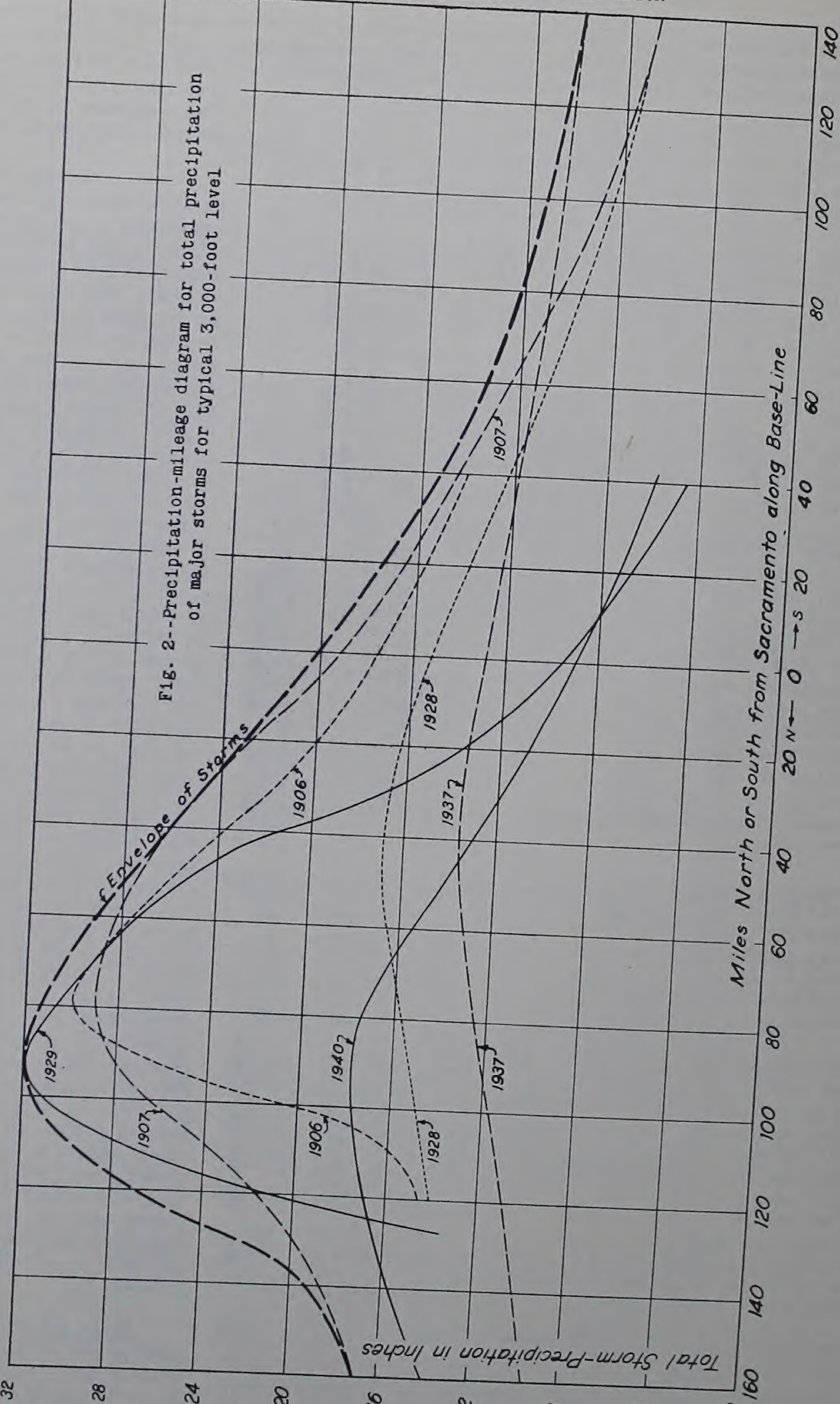

Fig. 2--Precipitation-mileage diagram for total precipitation of major storms for typical 3,000-foot level

trated in one or more short sub-periods, separated by long periods of little or no rainfall. These intense sub-periods can be connected with the passage inland of successive occluded fronts about one day's travel apart generated by a slow-moving storm-center over the Pacific Ocean. The

frontal action may produce about two inches of rain, but the accelerated movement of warm, moist marine air inland against the mountain slopes may produce as much as eight inches of rain a day by pure orographic action. The great gap through the coast ranges at San Francisco Bay allows the entrance of great volumes of this moist air into the Valley at the latitude of Stockton and produces exceptionally heavy rainfall on the Sierra slopes to the east and northeast of the gap, but occasionally the moving air-masses are so thick that they can hurdle the coast ranges along their entire length and produce heavy rainfall along the entire Sierra Nevada. This broad action was particularly noticeable in the storm of December, 1937.

As would be expected, there are more great storms than floods available for study and they are of more uniform size, indicating that they are approaching an upper limit that is valid for present climatic conditions. Preliminary isohyetal maps of total precipitation have been drawn for all the major storms of record in the Valley. Direct study of these complicated maps proved very difficult and it was necessary to break them down into simple factors before comparison and analysis could be made. An isohyetal map can be considered to be a topographic map of the precipitation-structure. Cutting vertical sections through this structure along the irregular trace of each 1,000-foot elevation contour of the underlying ground-surface will produce a curve which shows the variation of precipitation along the direction of the mountain range. When these sections are projected on the center-line of the Valley, a mileage-precipitation diagram is developed that is easier to analyze. Figure 2 shows a comparison of such precipitation-mileage diagrams for the typical 3,000-foot level for the greatest storms of record. Similar sets were drawn for other levels. A strong family relationship between the various storms is at once apparent. Each storm reaches a maximum over a belt about 30 miles wide and diminishes rapidly in intensity to the north and south. Furthermore, the farther north the maximum occurs the higher and narrower the storm is. It can be imagined, therefore, that if the maximum occurred at the head of the Valley near Kennett, the storm would reduce in width to a few miles and would be described as a cloudburst. The opposite extreme is the storm of December, 1937, which centers toward the south, and is very flat and sustained. Note that there is a persistent decrease in peak-precipitation toward the south. A smooth curve enveloping these individual storm-curves of total storm-precipitation probably closely approximates the upper limit for potential storms. This conclusion must be reinforced by studies of the maximum observed precipitation in single storm sub-periods coupled with a study of the potential number of such sub-periods that can be added together to make up a total storm. With the envelope-curve of storms of record increased by a modest factor of safety and with the observed transition in shape of individual storms as their centers progress north, it should be possible to design a synthetic storm that will produce the maximum possible precipitation over any subdivision of the Sacramento River Basin.

Ground-conditions--Let us now consider the factors which modify the precipitation after it reaches the ground. A flood-producing storm must fall on a wet, relatively impervious surface. As was observed for the precipitation of storms, the runoff-factors observed during great floods do not vary as greatly as the floods themselves and, by the end of a general storm-period, seem to approach an upper limit for this territory. A runoff-factor of 60 per cent on all area below the snow-line and 75 per cent on the effective area above that line seems to represent the maximum possible runoff-factors during general storms in this territory.

Contribution from melting snow--Because of the extreme height of the Sierra, there is always some snow on the ground when a major winter storm occurs and the flood is modified more or less by its presence. The concept of this snow as a wedge that extends down the mountain slope has proved most useful. The thin edge of the wedge is melted completely by the heat of the warm storm-air and rain and contributes at once to the runoff. Farther up the slope where the wedge is deeper, the snow is only partly melted and the rain and snow-melt have to make way through the porous snow-blanket to reach the stream-channels. The tremendously increased surface-storage delays and smooths the runoff-hydrograph and reduces the peak-runoff. Still farther up the slope, where the snow-wedge is more than four feet deep, all the rain and snow-melt are absorbed and no surface-runoff occurs. This area must be subtracted from the total area to give the effective runoff-producing area. The thin edge of this snow-wedge has been observed at various different levels in historical floods from the 3,000-foot level up to the crest of the Range. Hence it is probably the most variable of the flood-factors. Potentially, the snow-line could be at any level above about 3,000 feet. It is necessary to determine the worst position of the wedge for any particular drainage-area by successive trials. A convenient method of making these trials has been developed by the writer, but is too complex to be described in this paper. Numerous flood-studies along the Valley have led to the conclusion that, in most cases, the greatest floods occur when the snow-line is near the upper edge of the drainage-area and that rarely does the presence of snow increase the peak-runoff more than ten per cent although it may increase the flood-volume by 50 per cent.

Potential floods--Potentially, the maximum possible precipitation can occur as rain at least to the 10,000-foot level, can fall on a relatively wet and impervious surface, and can occur at the time when the snow-wedge is in its worst possible position. This has been the basic procedure used by the writer in estimating the potential floods on the major tributary streams of the Valley. And these estimated potential floods have not greatly exceeded the great historical floods, indicating that those floods are actually close to the upper limit for floods in the Valley and are better guides to design than had been hoped for.

This same procedure will soon be followed in the investigation of the still more difficult problem of estimating the potential flood on the main Sacramento River which combines the flood-runoff from all the tributaries. It is believed that no single storm could produce the maximum potential flood on each of the tributaries with just the right timing to combine into one super flood but that the worst that can be expected would be maximum floods on one group of tributaries combined with less-than-maximum floods from other tributaries. This study will inevitably require many, many trials and will be intensely interesting. I hope to report the results of this study at some future meeting of this Section.

U. S. Engineer Corps,
Sacramento, California

DISCUSSION

JOSEPH W. GROSS (Sacramento Municipal Utility District, Sacramento, California)--I am much interested, and have been, in the type of investigation which Mr. Parsons has discussed so well this morning.

There are several other engineers here who have been connected with earlier flood-studies of the Sacramento Valley. Mr. Givan, Mr. Bailey, and Mr. Blackie were investigating these matters prior to 1915. Naturally, there is considerable local interest in this general subject, and one item at least might be considered at greater length. Here Mr. Gross called attention to Mr. Parsons' envelope-curve of "Flood-runoff of Sierra Nevada streams." He went on to say that many storms coming down from the north turn and enter California from the south and west and that this series of storms could or should produce in northern California, at certain times at least, the same types of torrential runoff which have been experienced in southern California; that the absence of reported floods from storms of cyclonic type in this locality and their presence in the south offers an opportunity for the suggestion that when more complete records on smaller watershedsin northern California are available the data on peak-flows here should or could approximate the intensities experienced in the Los Angeles Area. He also stated that the group of watersheds, some of them at lower elevations, and with areas well under 1,000 square miles, might be of minor importance in the total runoff of the major Sacramento Flood-Control Project because the program was primarily one for the safety of lands in the valley-floor, but nevertheless they were of immense importance locally and knowledge of the peak-flows from smaller watersheds was of more than passing importance in the general consideration of floods. He inquired whether there was any reason to be certain that a greater knowledge of flood-flows could not be expected to develop additional data, which when plotted would fall well above the broken envelope-curve as now drawn for these watersheds of smaller area.

N. E. EDLEFSEN (University of California, Davis, California)--Mr. Parsons, you mentioned three features which theoretically determined the magnitude of the flood, one of which was the character of the storm and another one was the degree to which the retention of the watershed had been saturated at the time of the storm. I was wondering to what extent you regard surface-retention as a constant factor. Can we regard that as something which can be changed materially or is it constant?

MR. PARSONS--The retention is largely made up of surface-detention in the innumerable shallow basins scattered all over the area. Where there is snow packed in drifts, that also causes retention. Mr. Parsons was of the opinion that the percentage of constant surface-retention was subject only to small change even by artificial means.

MR. EDLEFSEN--Does that mean that you would conclude from your studies that the management of the range is not highly important in flood-control?

MR. PARSONS--Yes.

CHARLES J. KRAEBEL (Principal Silviculturist, California Forest and Range Experiment Station,

Berkeley, California) then entered the discussion and told of the work that had been done in mountain watersheds of southern California. He stated that it takes the chaparral 15 to 20 years to become fairly reestablished after being destroyed by fire, but that even under such cover erosion during severe storms may attain rates of 15,000 to 20,000 cubic yards per square mile of watershed. After severe burning chaparral sites often remain almost completely denuded for several seasons. For several years after fire the bare soil-surfaces between sprouting chaparral stumps, four to six feet apart, are exposed to severe erosion. (See page 130 for balance of Mr. Kraebel's discussion.)

EDWIN S. FULLER (Los Angeles Flood-Control Department, Los Angeles, California)--Referring to the storm of March, 1938, and the subsurface water, the water seemed to sink into the ground and then come out a few hours later, having a very decided effect on the runoff-hydrograph.

MR. LEE--The point made by Mr. Gross of the differences in intensities in the rainfall in southern California and this part of the State might make the difference in the runoff shown on the diagrams.

JOHN F. JOHNSTON (U. S. Department of Agriculture, Soil Conservation Service, Berkeley, California)--I want to supplement what Mr. Kraebal said about the possibility of doing something to add to the cover in the mountains, by referring to the treatment of valley-lands. The Department of Agriculture has been experimenting to increase the retention on agricultural and grazing lands and has determined that by the proper treatment of agricultural land we can materially increase the detention and infiltration. We are not ready yet to go into figures for publication but we think the increase is considerable. We believe that within a few years we will have demonstrated that this is an important factor with respect to runoff and deserves serious consideration with respect to drainage and flood-control.

OTTO MEYER (U. S. Engineer Corps, Sacramento, California)-- Our studies in connection with flood-routing indicate that in the Sacramento Valley there is no contribution from the valley-lands. The irrigation checks and furrows hold the water to some extent and drainage-ditches hold the balance in storage. Nothing comes into the River from that source. We cannot find any indication that floods are augmented by drainage from agricultural lands.

STORM-CHARACTERISTICS OF THE SACRAMENTO BASIN

Joseph B. Paulson, Jr.

(1) Development of storms--The winter storms which invade northern California originate through the interaction of Polar Pacific Air with Tropical Pacific Air. This happens when the polar low-pressure areas are forced farther south than usual or the semi-permanent high-pressure areas just north of the Hawaiian Islands break down. Waves induced along this polar front or discontinuity-surface between these two areas travel eastward across California. The passage of a family of as many as five such waves or storms has been noted. The development of the frontal system associated with these storms or low-pressure areas is accompanied by heavy precipitation from the moisture-laden Tropical Pacific Air.

(2) Frontal activity--The fronts of these storms usually are occluded by the time they reach the California Coast with the upper-level fronts proceeding easterly across the State. The warm-front type occlusion from the southwest or south-southwest yields the heavier orographic precipitation because it is usually accompanied by higher humidity. The cold-front type from the west is accompanied by higher winds but lower humidities. The average speed of the North Pacific lows during the winter season of December, January, and February, according to E. H. Bowie and R. H. Weightman, is 728 miles per day, or about 30 miles per hour. During the storm of December, 1937, the front of an occlusion of the warm-front type traveled across the northern part of the State in less than 12 hours. In this storm there were two such fronts about 36 hours apart.

(3) Types of precipitation--There is both frontal and orographic precipitation along the west slope of the low coast ranges as the warm Tropical Pacific Air is lifted over them. This process is followed by subsidence on the east slope of the coast ranges with the amount of precipitation decreasing rapidly so that this area yields comparatively little runoff to the Sacramento River. During the passage of low-level storms, a considerable amount of the tropical air enters the Sacramento Valley through the low passes in the Golden Gate Area without losing moisture by orographic action. The floor of the Sacramento Valley receives mostly frontal and convectional precipitation. When the warm tropical air climbs the Cascades and Sierra Nevada to the east of the Valley, there is again both frontal and orographic types, but this time the

orographic is larger than over the coast ranges because, with general crest elevations of 4,000 feet to more than 8,000 feet, the air is forced to rise much higher than before. After crossing these higher ranges, the air again subsides and the amount of precipitation declines rapidly in northeastern California and Nevada.

(4) Precipitation-centers and distribution--The larger precipitation centers in the Sacramento Basin appear to be near Kennett on the upper Sacramento River, and Inskip in the Feather River Area, with the center at Inskip usually having the highest precipitation. In the storm of March, 1907, it received more than 35 inches while Willows on the valley-floor just west of the Sacramento River received only 2.5 inches and Sacramento about six inches. In the recent storm of February, 1940, the Inskip Area received more than 23 inches, the Kennett Area about 14 inches, and Willows less than four inches.

(5) From a study of various storms it appears that, with a southwest or south-southwest wind behind the front, the Inskip and Kennett areas may each get a total of more than 30 inches, as in the storm of December, 1929. During this storm Kennett received 10.79 inches in 24 hours (December 12). Also, that, with a west-southwest wind, the distribution of precipitation would ordinarily be like that for the storm of February, 1940. With a west wind and a front running

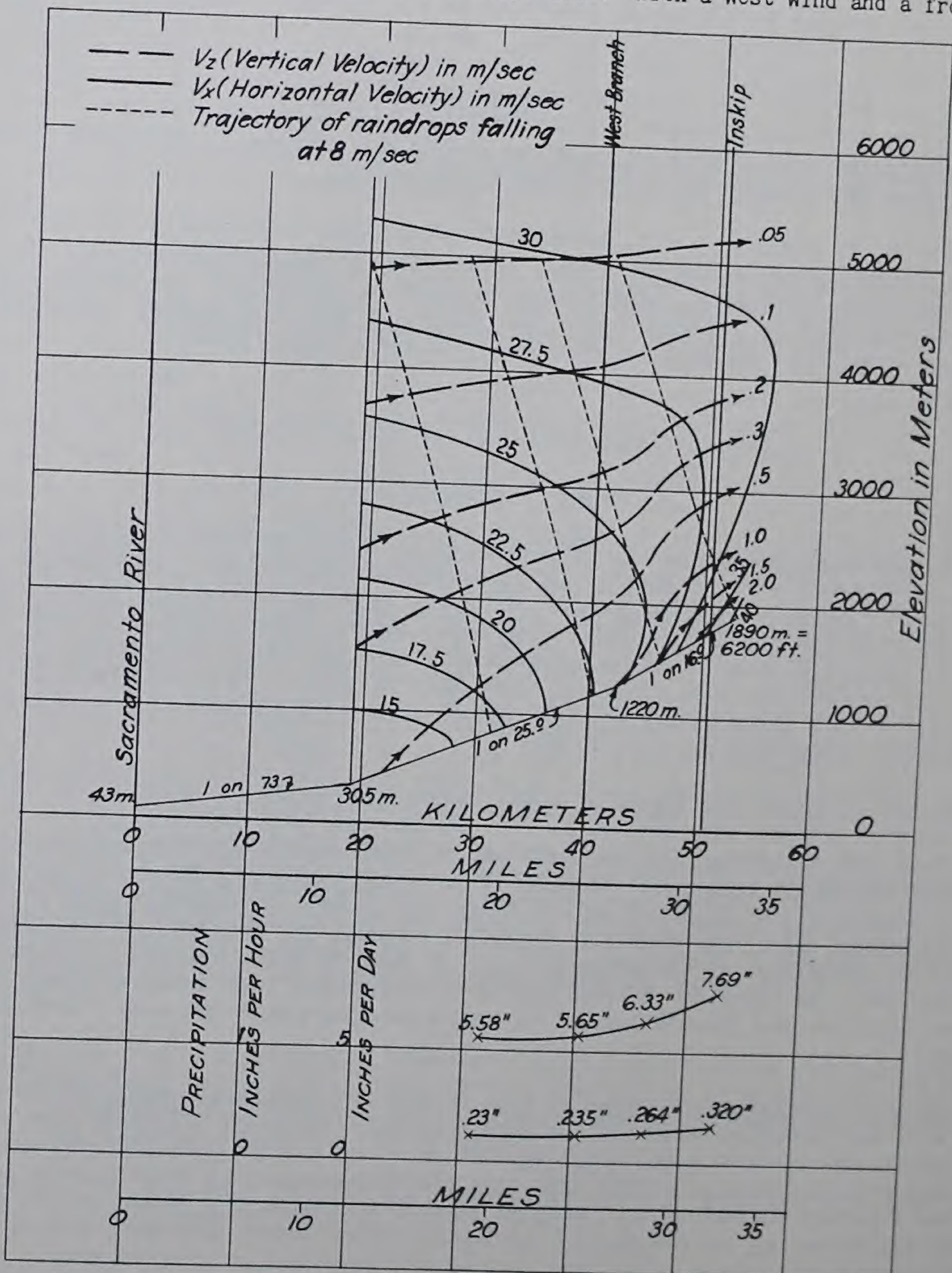

Fig. 1--Computed maximum orographic precipitation, mean section through Inskip in Sierra Nevada

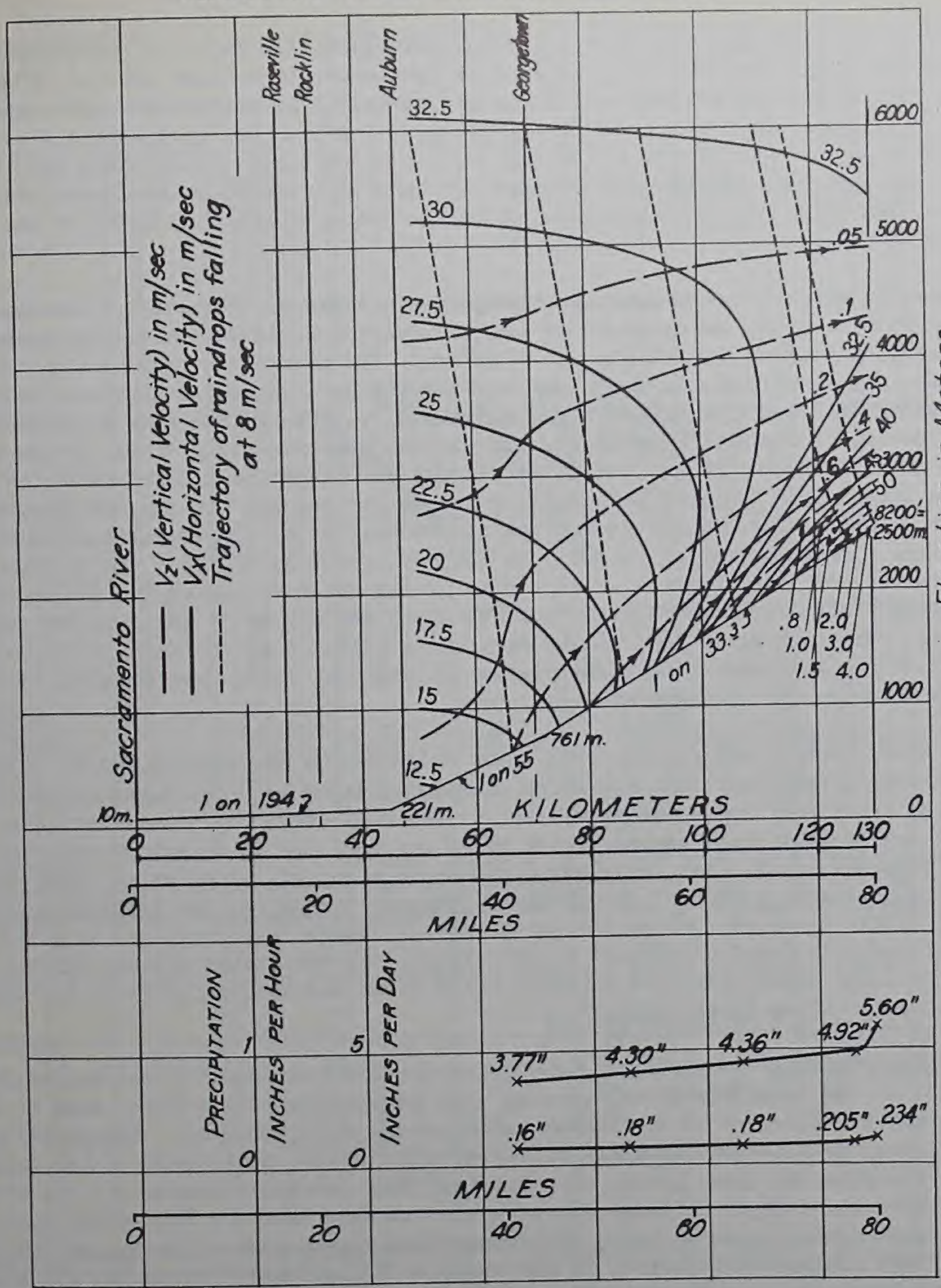

Fig. 2--Computed maximum orographic precipitation, mean section through Auburn in Sierra Nevada

north to south, the distribution may be heavy to the south of the Sacramento Basin with a precipitation center in the Summerdale Area and one in the Mt. Whitney Area.

(6) Orographic precipitation on the Sierra Nevada--I have made some calculations of the maximum steady orographic rainfall to be expected at two sections on the Sierra Nevada following a method used by Dr. J. Bjerknes for a section on the Sierra Madre. After an investigation of the Oakland air-sounding data and the Sacramento and Donner Summit wind-data, it was concluded that the same assumptions as to temperature, relative humidity, and wind-velocity could be used for the Sierra Nevada as for the Sierra Madre. These assumptions included the following: That the air-mass to be lifted was saturated at all levels, that it had a temperature of 16° C or 60° F at the ground, and that it had a horizontal velocity which increased from 20 meters per second or 45 miles per hour at elevation of 1,000 meters to 30 meters per second at elevation of 5,000 meters, that its vertical component of motion decreased exponentially from the mountain slope upwards, that its movement was at right-angles to the ridge, and that the maximum size rain-drops had a vertical velocity of eight meters per second. On the basis of these criteria, the maximum hourly rates of steady orographic rainfall and daily equivalents were calculated for various distances and elevations along generalized sections. These results are shown on Figures 1 and 2, which also show the lines of equal horizontal and vertical wind-velocities and the trajectories of maximum size rain-drops.

(7) It will be noted that, for corresponding elevations, the rates of orographic rainfall are greater on the Inskip Section (Fig. 1) than on the Auburn-Lake Tahoe Section (Fig. 2) and that at the summit of the Inskip Section, where the elevation is about 6,200 feet, the maximum calculated rate is about 0.32 of an inch per hour (or 7.7 inches per day) compared with 0.23 of an inch per hour (or 5.6 inches per day) at the summit of the Auburn-Lake Tahoe Section where the elevation is 2,000 feet higher. The reason for the higher rates on the Inskip Section results from the fact that its mountain slopes are about twice as great as those on the Auburn-Lake Tahoe Section.

(8) Now let us compare the maximum calculated daily rates of orographic rainfall with the maximum total daily rainfall observed by the United States Weather Bureau during a general storm. At Inskip, elevation 4,808 feet (1,465 meters), the calculated maximum orographic rate shown on Figure 1 is about 7.0 inches per day whereas the greatest observed daily total was 9.32 inches on December 10, 1937. At West Branch, elevation 3,216 feet (980 meters), the calculated amount from Figure 1 is about 5.6 inches per day and the observed daily total, probably a maximum, was 8.00 inches on December 10, 1937. At Georgetown, elevation 2,300 feet (700 meters), the calculated amount from Figure 2 is about 3.8 inches per day and the maximum observed daily total was 6.05 inches on January 14, 1909. The difference in the figures at each station indicates the minimum amount of frontal rainfall on the days referred to since the maximum calculated orographic rate may not have occurred on that day, or may not have lasted the entire day, and since the observed total figures are daily amounts which may not be as great as the maximum 24-hour figure. For instance, a preliminary mass-curve analysis of the data for the storm of December, 1937, indicates that the maximum 24-hour rainfall at Inskip was about 13 inches compared with the observed daily amount of 9.32 inches.

(9) Some other interesting results from these calculations may also be noted. First, the calculated horizontal velocity at an elevation of 9,000 feet on the Lake Tahoe Section (Fig. 2) which elevation is 800 feet above the summit and is probably above the zone affected by ground-friction, is about 74 meters per second or 165 miles per hour and is in accord with the testimony of air-pilots who report that they have encountered winds of 150 miles per hour over Donner Pass at elevations between 8,000 and 12,000 feet. Second, the calculated vertical velocity at the 8,200-foot summit is about four meters per second, a figure only about one-half the assumed rate of fall of the rain-drops of largest size. Third, the calculated minimum horizontal travel of rain from the 5,000-meter elevation is about 7-1/2 miles and is indicative of the carry-over at these summits, and along these slopes.

(10) Historical storms--To understand the potential-storm problems of the Sacramento Basin requires a study of the large historical storms. The preparation of isohyetal maps of such storms is in progress, a number of preliminary maps having been completed. The graphs shown on Figures 3 and 4 provide a convenient means of making preliminary comparisons of the larger of these storms. The data for these graphs were obtained from the daily records of the United States Weather Bureau and cover 12 large storms which occurred over the Sacramento Basin from 1900 to date. The precipitation is given for representative stations along the Cascades and Sierra Nevada. The stations are plotted as abscissas with their locations north and south of Sacramento being laid off along the bottom of the graph and their names and elevations along the top. The amounts of precipitation are plotted as the ordinates. Figure 3 shows the total storm-precipitation whereas Figure 4 gives the daily average as obtained by dividing the storm-total by the time required for its occurrence. The data on Figure 4 are intended as a measure of the intensity. While the accurate preparation of such graphs would require the construction of mass-curves of precipitation for each station and storm, a much abridged method has been found adequate for preliminary study and was used. In this method, the total elapsed time for passage of the main frontal systems of each storm was estimated to the nearest whole day from data readily available.

(11) Without trying to quote any figures, I will briefly describe these storms. First, let us look at Figure 3. It will be observed that the total precipitation in the storm of January 30 to February 3, 1909, centered north of the Kennett Area. That of December 8 to 16, 1929, centered near Kennett. The storm of March 16 to 26, 1907, had its largest center near Inskip, as did that of February 24 to 29, 1940. The storm of March 22 to 27, 1928, was heaviest south of Inskip near Donner Pass. That of January 12 to 19, 1906, had its largest center near Magalia in the Inskip Area. This is also true of the storm of January 12 to 17, 1909. Both had very heavy precipitation south to Donner Pass. The storm of February 3 to 11, 1916, was very limited in extent and centered at Magalia. That of January 9 to 16, 1911, extended from north of Nevada City to south of West Point. The storm of December 9 to 12, 1937, had a center near Inskip and another near Mt. Whitney. That of January 23 to 31, 1911, had a center at Magalia and a larger one at Summerdale. The storm of November 16 to 22, 1900, had its center at Summerdale. It will

Fig. 3--Comparison of precipitation, Cascades and Sierra Nevada

Fig. 4--Comparison of precipitation, Cascades and Sierra Nevada

be seen from a study of the precipitation-plot of the centers just enumerated that the larger storms over the Sacramento Basin have been those of December, 1937, March, 1907, and January, 1906. It is interesting to note that the amount of precipitation, which has fallen during the storms shown on Figure 3 on the area from Nevada City to West Point is considerably less than that which has been received to the north and south of it along the range. A study of the iso-hyetal maps for these and other storms indicates that, when there are precipitation-centers in the Nevada City-West Point Area, the amounts thereat are low in comparison to other centers in the same storm or to centers north or south of the Area in other storms.

(12) Figure 4 shows the average daily precipitation. It will be observed by comparison of this Figure with Figure 3 that the relative magnitude of the storms as measured by intensity is different than that measured by total precipitation. It is evident from Figure 4 that the most intense storms over the Sacramento Basin have been those of December, 1929, February, 1940, December, 1937, January, 1906, and January, 1909. Of these five storms, that of December, 1937, is the only one which had a very high center in both the Kennett and Inskip areas. Also, it had a higher average rate of precipitation at Nevada City than any other general storm. It is evident, therefore, that the storm of December, 1937, was not only the most general of the larger storms in the Sacramento Basin, but also the most intense.

(13) Potential storms and ground-conditions--We are now in a position to consider the problem of the maximum potential flood-producing storm and the ground-conditions preceding it. On the basis of our present records, it appears that complete frontal systems can pass over the Sacramento Basin with a spacing as close as 24 hours and that as many as five such storms can follow each other in a series. Such a storm-series would be materially longer than the concentration-period of the entire flood-producing portion of the Sacramento Basin. The precipitation produced by the passage of a single occlusion or complete frontal system appears to have been as much as 13 or 14 inches at Inskip with corresponding amounts at other points in the storm of December, 1937. The rain can be so wide-spread as to cover the entire Basin from the Calaveras River north to the head of the Valley and from the valley-floor up to the crest of the range. This is illustrated by several storms including March, 1907, and December, 1937. Such a storm can be preceded by a rainy period that will thoroughly wet the ground as illustrated by the storm of March, 1907, which was preceded by three weeks of rains. Antecedent snow-pack can cover any part of the drainage-area, as in January, 1907, but below the 3,000-foot level is normally not significant. Combining these various historical factors, it should be possible for the engineer to assemble a reasonable design-storm which would approach the maximum potential flood-producing storm over the Sacramento Basin.

U. S. Engineer Office,
Sacramento, California

DISCUSSION

C. B. MEYER (Associate Hydraulic Engineer, Division of Water Resources, Sacramento, California)--I see on the diagram that the orographic rainfall is increasing. Did it reach a maximum or is it still increasing?

MR. PAULSON--For these sections the rate of orographic rainfall is still increasing at the crest. We did not attempt to go beyond the scope of the calculations in Dr. Bjerknes' paper. The maximum computed rate of orographic rainfall will be near the crest on these sections. Just beyond the crest there might be more precipitation than at the crest due to carry-over. With a steep down-slope on the lee side, condensation will cease and the rain carried over will start evaporating. The computations on the lee side would be very difficult.

MR. MEYER--Then, the maximum shown on the chart occurs at the crest or near the same elevation.

MR. PAULSON--Yes, near the crest of the range on both of these simplified sections.

ROBERT L. WING (Associate Hydraulic Engineer, Division of Water Resources, Sacramento, California)--In that case, how does that check out with the information of yesterday which showed the maximum fall at the 4,200-foot level?

MR. PAULSON--My Figures 1 and 2 show the possible maximum rates of only steady orographic rainfall. They do not show the total orographic precipitation for any storm or year. Mr. Lee's graphs showed the total annual precipitation of all types and kinds. Therefore, Mr. Lee's in-

vestigations and these calculations cannot be directly compared. Mr. Paulson then discussed the action and speed of the air, horizontal direction of rain-drops, and referred to Dr. Bjerknes' paper.

L. STANDISH HALL (Hydraulic Engineer, East Bay Municipal Utility District, Oakland, California)--In my opinion, rainfall over the drainage-area is not the only element in creasing floods of large magnitude in the Sacramento Valley, but the air-temperature during the storm and the amount of snow on the ground prior to the storm also is a contributing factor. If cold storms have placed snow at low altitudes which is followed by a warm rain, the danger of a large flood is greatly increased. The greatest flood-danger occurs when there is less than four feet of snow over all or a large portion of the drainage-area. After the snow obtains a greater depth, warm rain serves only to compact the snow but does not yield a great deal of runoff. When the depth of snow is less than four feet and particularly when it is less than two feet in depth, a warm rain and the accompanying warm air-currents can frequently melt all of the snow. Observations have been made at an elevation of approximately 4,000 feet near Calaveras Big Trees of a depth of four feet of snow being entirely melted between weekly visits during a period of high temperature and warm rains. The large flood of December, 1937, was the result of a warm rain at a time when there was less than two feet of snow over a large portion of the Sierras. The same conditions occurred in 1928 during the large flood of that year. Prior to the warm rain in the latter part of March, there had been a maximum of only four feet of snow accumulated on the higher altitudes of the watersheds. This rain melted most of the snow, with the result that very large floods occurred. Prior to the occurrence of the flood of 1928, there was a general belief among engineers that a major flood could not occur in the year of subnormal runoff. In the floods of 1861-62 the reports available indicate that there was snow at very low elevations in the foothills prior to the storm. There were really three major floods in that year; one in December, 1861, and two in January, 1862, where warm rains melting snow augmented the runoff [Sacramento Flood-Control Project, California State Reclamation Board, revised plans of 1925, pp. 109-115]. To be sure, rains of unprecedented volume occurred at the same time. Without citing further examples, it can be stated as a result of observations of the snow-pack and meteorological conditions accompanying large floods that whenever the snow is at low altitudes in the foothills and a warm rain of great intensity occurs, these are the conditions that produce the maximum flood-runoff.

WALTER J. PARSONS, JR. (U. S. Engineer Office, Sacramento, California)--Very low snow certainly could produce extremely bad floods in the foothills. But to have this right amount of snow in the foothills, do you not invariably get heavy snow in the higher areas so you get a flood from only one portion of the drainage-area? Are not those two things tied together?

MR. HALL--It must also be born in mind that the snow-cover at the higher elevations must be less than four feet in depth in order that the warm rain and warm air can complete the melting of the entire snow-pack. It is believed that sufficient evidence has been cited to support my contentions.

ALBERT GIVAN (Sacramento Municipal Utility District, Sacramento, California)--It is a well-known fact that a heavy snow-cover in the high Sierra has been an influence in suppression of flood-conditions.

J. E. CHURCH (Nevada Agricultural Experiment Station, University of Nevada, Reno, Nevada)--At the 8,400-foot elevation in the Sierra at Lake Gross, we found on April 1 that the snow-cover of 184.6 inches had a 69.3-inch water-content (density 37.5 per cent), was saturated and just beginning to lose the water after the entire winter. That gives you an idea of the retention-power of the snow-blanket under continuous warmth.

FLOOD-ROUTING ON THE SACRAMENTO RIVER

Otto H. Meyer

Introduction--The flood-problem in the Sacramento River System is one in which the people of the Central Valley of California are vitally interested. A large proportion of the agricultural land of the Valley is reclaimed swamp and overflow-land. Although many millions of dollars have been spent on reclamation and flood-control, recent floods have indicated the need for further study. In order to determine the adequacy of the present system of levees and by-passes, and to plan intelligently on future improvements, it is necessary to know the behavior of past and future floods. Therefore, a restudy of past floods has been made by routing these floods through the present system and possible modifications thereof. The results of these routings

will furnish an excellent guide in predicting the probable future frequency of flows of any magnitude in any part of the system.

Previous routings--The necessity of routing to obtain essential information for flood-control studies has been recognized for many years. The earliest flood-routing computations on the Sacramento River were undertaken by the State of California. Prior to the present studies described in this paper, the most recent investigations were those made by the Corps of Engineers

Fig. 1

of the War Department in 1931 in connection with a comprehensive study of the Sacramento River with respect to flood-control, navigation, irrigation, and power-development. In the studies of 1931, which were made under the direction of R. D. Goodrich, all floods of record up to that time were routed through the river-system. Since that time, major floods have occurred in 1937, 1938, and 1940, as well as minor floods in 1935 and 1936. Because of these recent floods, and the improved technique recently developed in flood-routing, together with the fact that flow-conditions have changed in certain localities, a routing, more comprehensive than any previously undertaken, is now warranted and justified.

Description of the System--For the purposes of this paper, the term "Sacramento River System" is used to refer to that portion of the River and of its tributaries lying within the alluvial valley, as shown on the accompanying map (Fig. 1). The Sacramento River enters the northern extremity of the Valley at Red Bluff. Small creeks continue to add to the flow down to Chico Landing, where Chico and Stony creeks enter on opposite sides. Below here the River has built itself an alluvial ridge, flanked by broad, low basins into which it has overflowed for ages. The channel becomes progressively smaller downstream, diminishing from a capacity of about 200,000 cfs at Red Bluff to only 20,000 cfs at Knignts Landing. The basins flanking the River are separated by higher ground at intervals. The Butte Basin, on the left bank, is terminated by the Marysville Buttes, a volcanic intrusion. South of the Buttes is the Sutter Basin, lying between the Sacramento and Feather rivers. On the right bank is the Colusa Basin, terminated by Knights Landing Ridge, which is the old alluvial ridge of Cache Creek. South of this ridge is the Yolo Basin, which extends to tidewater. Between the Feather and American rivers is the American Basin, and below the American River is the Sacramento Basin. In order to reclaim the basins for agriculture, levees were built along the river-banks. However, the channels between the levees were not adequate to contain the flood-waters poured into them, so a system of by-passes was constructed to carry the excess waters. The river-bank along the upper end of the Butte Basin was left unobstructed, allowing flood-waters to flow out of the River and down the trough of the Basin, which is yet relatively undeveloped. The lower Butte Basin forms a pool, or reservoir, into which the water flows from the upper Butte Basin, and from the River at Moulton and Colusa weirs. From this pool the water flows past Mawson Bridge into the upper end of the Sutter By-pass. The latter consists of a strip of land about 4,000 feet wide skirting the east side of the Sutter Basin trough to join the Feather River a few miles above its mouth. The by-pass then continues parallel to the Feather River until it reaches the Sacramento River, where excess flood-waters cross the channel and flow over Fremont weir into the Yolo By-pass. The Tisdale By-pass carries water escaping over Tisdale Weir across the Sutter Basin to join the Sutter By-pass at about its midpoint. The Yolo By-pass, on the west side of the River, is joined by the Sacramento By-pass opposite Sacramento, and rejoins the Sacramento River a short distance above Rio Vista.

Organization--The first step in preparing for the routing was to organize the System into reaches. The location of reaches was based on major inflows, critical points, and check-points. Stream-junctions and points where the flow divided, as at the various weirs, were designated as critical points while those points where routed flows could be checked by actual gage-records were designated as check-points. A glance at the map shows that the following are critical points on the Sacramento River: Chico Landing, the point where the last of a group of minor creeks enters and where the first flow out of the River (Butte Basin overflow) occurs; Moulton Weir, the first weir-structure; Colusa Weir; Mawson Bridge, to which flows in Butte Basin converge; Tisdale Weir; the junction of the Sacramento and Feather rivers with the Sutter By-pass, where the flow then divides to go over Fremont Weir into the Yolo By-pass and past Verona down the Sacramento River; Sacramento Weir and the mouth of the American River; and the junction of the Sacramento River with the Yolo By-pass above Rio Vista. On the Feather River, critical points are at Marysville, where the Yuba River enters the Feather, and Nicolaus, just below the mouth of the Bear River, where the Feather River meets the Sutter By-pass.

The check-points, where gages are located, include most of the above critical points, and also Butte City, Colusa, Knights Landing, and Sacramento at I Street, all on the Sacramento River; Gridley, on the Feather River; and Lisbon, in the Yolo By-pass. Other gages within the System proved valuable though not affecting the organization for routing.

Inflows into the System were generally taken at the foothill-line. The major inflows are the Sacramento River at Red Bluff, the Feather River at Oroville, the Yuba River near Smartsville, the Bear River near Wheatland, and the American River at Fair Oaks. Others of some magnitude are Cache Creek near Yolo, Putah Creek near Winters, and the Knights Landing Ridge Cut, which is an artificial cut draining the Colusa Basin. Complete records of the flows from these sources of inflow are available for a period of about 37 years, except in the case of the Ridge Cut, which was constructed about 1914, and has not been gaged due to backwater-difficulties and its relative lack of importance. Flows through this cut have been estimated.

Other inflow, classed as local inflow, comes from a number of small streams, some of which enter the River between Red Bluff and Chico Landing, some enter the Butte Basin, and one, Honcut Creek, enters the Feather River below Gridley.

A consideration of the major inflows, critical points, and check-points led to the choice of the following reaches for the routing: On the Sacramento River, Red Bluff to Chico Landing, Chico Landing to Butte City, Butte City to Moulton Weir, Moulton Weir to Colusa Weir, Colusa Weir to Tisdale Weir, Tisdale Weir to Knights Landing, the junction of the Sacramento and Feather rivers with the Sutter and Yolo by-passes (hereafter referred to as Fremont Pool), Verona to Sacramento (this reach was not routed as it acts principally as a balancing pool for Sacramento Weir and the mouth of the American River), and Sacramento to Rio Vista. On the Feather River, reaches were chosen from Oroville to Gridley, Gridley to Marysville, and Marysville to Nicolaus. Other tributary reaches included the Yuba River from Smartsville to Marysville, the Bear River from Wheatland to its mouth, the American River from Fair Oaks to its mouth, and Putah Creek from Winters to Lisbon. Reaches in the by-passes consisted of the upper Butte Basin from Chico Landing to Moulton Weir, the lower Butte Basin from Moulton Weir to Mawson Bridge, the Upper Sutter By-pass from Mawson Bridge to the Tisdale By-pass, below which the Sutter By-pass becomes part of Fremont Pool; and the Yolo By-pass from Fremont Weir to Sacramento By-pass, from Sacramento By-pass to Lisbon, and from Lisbon to the vicinity of Rio Vista.

Determination of local inflow--The local inflow entering the Sacramento River between Red Bluff and Chico Landing consists of a number of small creeks. These were arbitrarily divided into a Red Bluff Group, the combined flow of which was assumed to enter the River at Red Bluff, and a Chico Landing Group, whose combined flow was assumed to enter at Chico Landing. A third group, flowing directly into the upper end of the Butte Basin, was designated the Butte Basin Group. Honcut Creek, which joins the Feather River below Gridley, was treated separately.

Some of the creeks in these groups have long discharge-records, others have shorter records, and some have no records whatever. The combined discharge of each group during each flood to be routed was needed. Two methods have been used to compute this contribution, namely, one by unit-hydrographs, the other by correlations.

In the unit-hydrograph method, a synthetic unit-hydrograph was prepared for each of the local inflow-streams. No great refinement was attempted, as the exact shape of the hydrograph of local inflow was lost when it was added to the enormously greater main river-flow. In preparing these unit-hydrographs, the drainage-area was accumulated from mouth to headwaters; the mass-curve of area was given a time-scale by applying an assumed stream-velocity; and this curve was then converted into a unit-hydrograph by methods described by the writer in a paper "Analysis of runoff characteristics" [Trans. Amer. Soc. Civ. Eng., 1940]. The writer is of the opinion that direct addition of unit-hydrographs of successive storms is theoretically not permissible, even though it has become a generally accepted practice. However, since the precipitation-pattern in this region is characteristically one of 8- to 12-hour storms beginning at about 24-hour intervals, the tail of the unit-hydrograph of one of these small foothill-streams has dropped so low at the end of 24 hours that, regardless of theory, its direct addition to the following hydrograph introduces little error. The unit-hydrographs were computed to represent the runoff from a storm of about 12 hours' duration.

The fact is now rapidly gaining recognition that in addition to surface-runoff, which is represented by these unit-hydrographs, subsurface-flow must also be considered. This is water which, while it enters the ground, does not reach ground-water and reappears in stream-channels within a few hours, sometimes before cessation of the storm. The hydrograph of this subsurface-flow is similar to that of surface-runoff. The rising limb is, however, so concealed by the hydrograph of surface-runoff as not to be distinguishable. From a careful study of existing records it was concluded that this flow will increase at a constant rate for about 48 hours after the start of the storm, and that it will then recede at a rate expressed by a reduction each 24 hours to 78 per cent of its previous rate. Best results were obtained when the subsurface-runoff factor was assumed to be one-half of the surface-runoff factor less 25 per cent. Thus, with ground-conditions so dry that the surface-runoff is less than 25 per cent, no subsurface-flow will occur. Using this assumed runoff-factor and shape of the subsurface-hydrograph, in conjunction with the previously mentioned unit-hydrographs of surface-runoff, actual hydrographs of some of these streams were reproduced reasonably well.

In the correlation-method, factors were determined correlating the discharge of neighboring creeks of similar characteristics. These factors were derived from actual discharge-records where such were available; otherwise they were derived from the corresponding unit-hydrographs. The discharge of a creek with known flow was then multiplied by the correlation-factor to get an

approximate figure for the discharge of a creek without discharge-records. In periods for which records are available on most of the creeks, only small proportional errors in the total are introduced by rather rough correlations. Where practicable, the correlation-method was used since hydrographs developed therefrom are probable superior to those derived by means of unit-hydrographs.

Between Red Bluff and Chico Landing, and in the upper end of the Butte Basin, there are considerable areas of valley-land, which drain directly into the River and are not tributary to the foothill-streams. The runoff from these areas had to be estimated. This land is largely hummocky, with many shallow depressions and poorly defined drainage. A comparison of rainfall with the runoff attributable to this area indicates that when dry conditions prevail, up to two inches of infiltration and surface-detention must be satisfied before runoff occurs. When run-off does occur it reaches the River within a few hours. The soil is tight, and infiltration slow, so that the recovery of surface detention-capacity is largely by evaporation. The ponds that form during storms often remain for weeks before drying up. After a consideration of the foregoing items, it was assumed that, at the beginning of a rainy period, two inches of detention-capacity would be available, that the capacity filled by rains would be recovered at a rate of 0.2 inch per day while under 0.6 inch, at 0.1 inch per day between 0.6 and one inch, and at 0.05 inch per day from one to two inches. The variable rate corresponds to the variable surfaces from which evaporation takes place. After the detention-capacity is filled, all additional rain will run off, reaching the River within 24 hours.

Flow-lines and division of flow--In order to determine approximately the volume of water in each reach at any discharge, and to determine the division of flow at the various weir-diversions, flow-lines were computed in the river-channels and by-passes. For this purpose, Manning's formula was used, with values of n assumed according to conditions, and with hydraulic elements computed from cross-sections taken from available surveys and maps. With starting elevations taken from rating curves or estimated, flow-lines were computed in each reach for various discharges. The elevations of the flow-lines at the upper ends of the reaches gave points on computed rating-curves at those places. These were checked with known rating-curves where possible, and adjusted to fit them. At the various weirs, the flow-lines were compared with elevations computed for the same discharges by weir-formulas to determine whether the weirs were affected by backwater. A comparison of a rating curve at a weir-diversion with one of the main River immediately downstream from the diversion determined the discharge going each way at any elevation, and permitted construction of diagrams showing at each diversion the division of flow for each value of total discharge above the diversion.

Development of storage-curves--Data obtained from flow-line computations permitted computation of the volume of water in a reach for any discharge. From this information preliminary storage-outflow curves were drawn. It was originally intended to use these curves for the subsequent routing, but just as the work reached this stage the flood of February to March, 1940, occurred. It was obvious that it would be necessary to reproduce this flood by routing. At the same time, the data collected during this flood, together with data from the flood of December, 1937, made possible the development of empirical storage-curves, which are greatly to be preferred to storage-curves developed from flow-line computations.

If the inflow- and outflow-hydrographs of a flood are known, the storage-outflow curve can be derived from them. The change in storage in any period is the difference between the inflow and the outflow during that period. These differences are accumulated, and the cumulative totals are plotted against corresponding outflows. The resulting loops indicate the shape of the storage-curve.

Complete gage-records having been collected in the floods of 1937 and 1940, hydrographs were known for all points for which rating curves were available. However, at many stations the records consist of gage-heights alone. For these points, rating curves and storage-curves were developed by the following method. First, using the known hydrographs at an upstream-station, the floods of 1937 and 1940 were routed through the reach below by means of the preliminary storage-curve mentioned before. Then the routed outflows were plotted against recorded gage-heights. An average curve was drawn through the plot. From this approximate rating-curve and the gage-records, new outflow-hydrographs were derived, and from these and the inflows an improved storage-curve was constructed. This process was repeated until no further change in rating curve or storage-curve resulted, the process being a convergent one. The rating curves developed in this manner are equal in accuracy and may be superior to those developed from discharge-measurements. Of course, the curves do depend on the correctness of the rating of the upstream-station. Fortunately, in this case, the United States Geological Survey Station at Iron Canyon near Red Bluff has an excellent rating-curve. Also, as the process was carried to successive reaches downstream, there were scattered measurements to check on.

That the construction of the storage-curves previously described is adequate may be judged from the fact that their use in routing has reproduced accurately both of the recent major floods.

A description of some of the peculiarities encountered in this development of storage-curves and in the routing of the floods of 1937 and 1940 may be of interest. One of these peculiarities concerned the Butte Basin overflow between Chico Landing and Butte City. This overflow occurs throughout most of the reach, and the question arose as to how great the overflow was and whether it should be deducted from the inflow or outflow of the reach. Flows were routed through the reach, and Butte City flows from a tentative rating-curve were deducted. The differences, which were the overflows, were plotted against the routed outflows. Then inflows necessary to produce the Butte City flows were computed by reverse routing, or "unrouting," and were deducted from total inflows, and the differences were plotted against total inflows. The latter gave the better correlation and was adopted. In fact, subsequent investigation indicated that most of the overflow does take place at the upper end of the reach. All of the above was done simultaneously with the development of the Butte City rating-curve and storage-curve for the reach. It was a complicated operation.

When routing was undertaken with the finally adopted rating- and storage-curves, it was found that the computed discharge at Butte City was too high after the crest of the flood. In the case of both the floods of 1937 and 1940, it was found that the separation of the routed and actual hydrographs occurred at the times when levee-breaks occurred in the reach above Butte City. It was obvious, therefore, that the difference resulted from the loss of water through the breaks. The conclusion as to this phenomenon was further supported by the fact that the differences in discharge disappeared as soon as the stage fell below bankfull, when the levee-breaks would of course cease flowing. The same effect occurred also at Moulton Weir, presumably as the result of breaks in the reach between Butte City and Moulton Weir.

While the effect of the levee-breaks near Butte City on the routing was incidental, that was not the case with the breaks in the levees of Reclamation Districts 70 and 1660, where a great volume of water was abstracted from the hydrograph and subsequently returned with such suddenness as to cause a second flood-crest in Sutter By-pass nearly as great as the first. The districts referred to lie between the Sacramento River and Sutter By-pass and north of the Tisdale By-pass. District 70 is the northerly of the two. The Sutter By-pass Levee of District 70 broke just below Mawson Bridge at the peak of the flood of 1940, and the Tisdale By-pass Levee of District 1660 broke near Tisdale Weir at the same time. There are gages in the Sutter By-pass both at Mawson Bridge and at Long Bridge, below the break in District 70. Measurements of the discharge at Long Bridge were used to rate both gages. After the break the differences in the hydrographs of the two gages gave a good indication of the flow through the break, which reached about 68,000 cfs. At the break of District 1660, estimating the inflow was more difficult. Fortunately temporary gages, in the form of crudely marked laths, were set up within both districts shortly after the breaks. These soon read within 0.2 foot of each other. From one-foot contour maps of the districts a stage-storage curve was constructed, and changes in stage indicated the total inflow. Deducting the break-flow of District 70 gave the flow into the break of District 1660, which reached a maximum of 70,000 cfs. The districts soon filled completely, to a maximum of 440,000 acre-feet, and, with falling river-stages, the levees broke outward in seven additional places. The maximum outflow was estimated from stage-changes to have been 123,000 cfs, while a total of 50,000 cfs was still flowing in through the break of District 70 at the upper end of the Basin.

Another place where the development of storage ran into peculiarities was at Fremont Weir. Routing indicated a rating curve with a peculiar hump in it. A weir-formula gave a shape that was similar except that it did not have the hump. A field-investigation showed that on the riverside of the Weir (which is a low concrete structure with a level crest at about the same elevation as the river-bank) there was a small mound of earth several feet higher than the weir-crest and topped with brush. This was the cause of the hump in the rating curve, of which we had been rather dubious.

Routing--After the storage-curves were completed, the floods of 1937 and 1940 as they occurred having been routed in the process, these floods were routed as they would have occurred if the levees had not failed. Routing was then begun on other floods until finally all floods of damaging magnitude since 1902 had been routed under conditions of 1940. These floods have also been routed as they would have been modified by an assumed scheme of operation of Shasta Reservoir. This entire series of floods will also be routed with other possible schemes of operation of Shasta Reservoir and possibly with other regulation or modification of the Flood-Control Project.

In doing this routing, three methods have been used. In most cases, where the time-lag from the occurrence of a storage in a reach to the occurrence of the corresponding outflow was three hours or more, the lag-method of routing was used with six-hour time-intervals. (For details of this method see "Simplified flood routing" [Civ. Eng., p. 306, May, 1941].) Where the lag was too short for lag-routing, the Steinberg method was often used. The third method was the use of a flood-routing machine, which was designed and built for this purpose. It is a graphical integrator. The inflow-hydrograph and the storage-curve are plotted and the plots are placed on the machine. When these are followed with pointers, the machine draws the outflow-hydrograph. For reaches where there is a considerable lag from storage to outflow a family of storage-curves, with the inflow as a parameter, is used on the machine instead of a single storage-curve. The machine competes with lag-routing on about an even basis, the time to plot the hydrographs for use on the machine being nearly that required for a lag-routing computation. The Steinberg routing has been almost entirely displaced by the machine, with considerable saving of labor.

Results--The routing described here has provided the equivalent of a complete discharge-record of 37 years at practically every point in the System. With this record, studies of flood-damage and flood-control benefits can be based on definite figures of discharge. Frequency-studies to determine the future probability of floods of any magnitude can be made for any desired point within the System. The magnitudes of the great floods of 1907 and 1909 at points in the lower Valley are now definitely known so that the adequacy of existing works can be determined accurately.

While the writer makes no claim for perfection in the results attained, it is evident that, through the additional data now available, engineers are in a better position than ever before to consider improvements in the control of floods in the Sacramento Basin.

U. S. Engineer Department,
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DISCUSSION

ERNEST A. BAILEY (Hydraulic Engineer, Sacramento, California)--My recollection of the floods in the Sacramento is that some come through quickly and some take a long time. In Texas some floods would go through in a couple of weeks and some in a month. I do not notice anything relating to rates of travel of different floods.

MR. MEYER--The time of travel of a flood-crest depends on the shape of the flood-hydrograph and the manner in which it is acted on by storage. It is not in any sense wave-motion. As the crest of a flood is reduced by storage, a portion of the hydrograph originally later than the crest becomes the crest at a downstream-point. This shift is greatest if the flood crests at a stage where the change of storage with change of stage is a maximum. It also depends on whether the flood is sharp or flat-crested, sharp-crested floods being affected more. In the Sacramento River, the travel of the crest from Red Bluff to Sacramento has varied between two and four days in some of our larger floods.

FACTORS INFLUENCING RUNOFF DURING THE FLOOD OF DECEMBER, 1937, IN NORTHERN CALIFORNIA

W. G. Hoyt (Read by R. C. Briggs)

Engineers and hydrologists engaged on flood-problems throughout much of the United States east of the Rocky Mountains must deal to a considerable extent with wide-spread storms covering thousands of square miles. The gradations of meteorologic conditions as regard both area and time are relatively homogeneous during such storm-events and are affected but moderately by orographical influences. Under such conditions similar storm-characteristics prevail over vast areas. True, precipitation decreases toward the boundaries of such major storm-areas, and locally precipitation-rates may greatly exceed the average. Often, however, drainage-basin after drainage-basin will yield comparable depths of flood-runoff. The storms of March, 1936, which resulted in the simultaneous occurrence of floods throughout all of the northeastern part of the United States from Ohio and Virginia to Maine and the storm of January, 1937, which embraced all of the 200,000 square miles comprising the Ohio River drainage are typical of major Eastern disturbances. The storm of December, 1937, in the Sacramento and San Joaquin valleys is used herein to illustrate what may be called a typical major California disturbance, and it is this storm

and resulting flood that I wish to consider in some detail and also to make such comparisons and contrasts with Eastern floods as seem to be of general interest.

It should not be inferred that the laws governing meteorologic and hydrologic phenomena in California are different from those in other parts of the country. They are not. The laws are the same but the conditions which control the phenomena are vastly different. Consider the 200,000 square miles comprising the Ohio River Drainage-Basin. The greater part of its drainage-area lies between altitudes of 500 and 3,000 feet and entirely in the humid zone. At no place is the average annual precipitation less than 35 inches and very little of the area receives in excess of 50 inches. Relatively speaking, when it is winter in one part of the Basin, it is winter throughout. Most of the storm-tracks that cross the United States from west to east roughly parallel the main axis of the Ohio Valley and the Basin is nearly meteorologically homogeneous with respect to storm-characteristics. On the other hand, take a small area such as the 1,000 square miles on the western slope of the Sierra Nevada drained by the Merced River above Exchequer, California. The altitude spread from 400 feet to over 13,000 feet results in a series of zones in the Basin ranging from semi-arid to humid and from subtropical to frigid, each with its own soil, vegetative cover, and physiographic features. To a greater or less degree each sub-basin making up the combined Sacramento and San Joaquin River drainage-basins includes wide ranges in soil, cover, and physiographic features. The relief characteristics not only result in wide differences in rainfall but actually control meteorologic events. As Dr. Matthes, in his classic work describing the Yosemite Valley of the Sierras, says "They are the author of their own weather."

Thus when on December 7 to 10, 1937, a moist Polar-Pacific air-mass, which had been modified by its passage over the relatively warm Pacific, moved inland and across northern California the heavy rains that resulted were almost entirely due to orographic effects, there being little indication of frontal action with other air-masses. In other words, instead of storm-precipitation falling with comparatively equal intensity over all the Sacramento, San Joaquin, and coastal drainage-basins, the total storm-precipitation was about six to eight inches along the coast, increasing to approximately 20 inches in places along the summit of the coastal hills, decreasing to two to four inches over the central valley, increasing again to about 20 inches in the 4,000- to 6,000-foot zone along the western face of the Sierras, and decreasing again to about two inches at the eastern base of the Sierra escarpment, all in the course of 200 miles.

Variations in rainfall such as described naturally produce wide variations in runoff-characteristics. If, however, there are introduced in this picture the equally great differences of soils, vegetative cover, slopes, geology, and related factors in the area under consideration, the difficulties which are encountered in storm-flood analyses in California on an areal basis are readily apparent. Although, in cooperation with the staff of Mr. McGlashen's office, I assisted in the preparation of the isohyetal map of the storm of December 9 to 12, 1937, as published in Water-Supply Paper 843, and made some studies of rainfall-runoff-altitude-temperature relationships, I would hesitate to vouch for the accuracy of the isohyetals or other interpreted data at any point much removed from a point of actual observation. On an areal basis over the central valley-floor and perhaps along the coastal region, the storm-precipitation is fairly well known. Along the coastal range privately kept observations were very useful in constructing the rainfall-map. However, it may not be amiss to mention that the rainfall-records officially compiled gave absolutely no indication of the severe storm-conditions which must have existed in the headwaters of Putah Creek and Russian River to cause their unusual flood-stages. Further search produced precipitation-records that clearly indicated rainfall of sufficient magnitude to account for the outstanding floods. Such a situation rarely occurs in an Eastern area with similar areal rain-gage distribution because it is probable that at least one gage would have indicated the presence of a severe storm-center, even if its magnitude were not clearly defined. Moreover, I would hesitate to hazard a guess as to the number of rain-gages which would be required to define accurately isohyetals along the western front of the Sierras during any individual storm. The group working on the study concluded in general that the precipitation probably increased quite uniformly at a rate of about three inches per 1,000 feet up to an altitude of about 5,000 feet. Above 5,000 feet the rate of increase or decrease of precipitation was almost anybody's guess. This situation has been greatly improved since 1937 through the installation of more rain-gages and especially recording gages at strategic points throughout California by the United States Engineer Department and the United States Weather Bureau.

In view of the various conditions outlined, it is obviously difficult to translate the observations of spot-rainfall or spot-temperature into values that are representative of entire drainage-areas or of an individual stream-flow station in to values that are representative of specific zones. Through detailed analyses, however, consistent trends were generally disclosed from which conclusions believed to be fairly reliable could be drawn. Some of these general

conclusions may be of interest and value to those engaged in flood-control problems, either through operations designed to control water after it has reached defined stream-channels or in operations designed to retard or dissipate runoff before it reaches stream-channels.

Effect of antecedent conditions--One of the striking conditions which is immediately disclosed by an analysis of rainfall-runoff relations in California is the magnitude of the influence of antecedent rainfall. It can almost be stated as an axiom that in much of the East the maximum flood-potentialities will always be associated with the largest storm. This condition does not obtain in much of California where in basin after basin natural storage-capacity of the soil over wide areas ranges from six to perhaps as much as 20 inches in contrast to the East where four to six inches seems to represent about maximum retention-capacities. The basic reason for this difference probably relates more largely to climatic conditions than physiographic features. In any region which is characterized by a relatively short rainy season followed by long rainless periods, it is but natural that there would be wide extremes in conditions of field and soil-moisture. During your long hot rainless periods, every available drop of moisture is wrung from the ground with the result that a very considerable portion of the water associated with storms which occur near the beginning of the rainy season is used to satisfy field-moisture deficiency. During the flood of December, 1937, retention-capacity as measured by the differences between rainfall and runoff exceeded eight inches in parts or all of the drainage-basins of Campbell, Stevens, Guadalupe, Los Gatos, and Uvas creeks at the southern end of San Francisco Bay; of Arroyo Seco in the Salinas Basin, San Lorenzo River on the Coast; and Tuolumne, Merced, Kings, Kaweah, and Fresno rivers in the San Joaquin Valley. In Alameda Creek Basin and in the lower parts of the Salinas, Tuolumne, Stanislaus, Calaveras, Mokelumne, and San Joaquin river-basins the total rainfall December 7 to 12 was apparently not even sufficient to afford a measure of their retentive capacities. In parts of the upper Kings, San Joaquin, Tuolumne, Feather, Yuba, and American river-basins the retention ranged from six to eight inches. In the High Sierra country average retention seems to have been between four and six inches. It may be of interest to point out that during the storm of March, 1936, in northeastern United States the retention was less than three inches in nearly all river-basins for Virginia, Maryland, Pennsylvania, New York, and New England; in California during the storm of December, 1937, retention of less than three inches was the exception and not the rule. Superficial analysis of some of the major floods in California seems to indicate that there may be better correlation between the magnitude of the antecedent rainfall and the flood-runoff than there is between storm-rainfall itself and the flood-runoff. Further analysis of the influence of antecedent rainfall in satisfying natural storage-capacity and thus limiting the capacity available for subsequent storms offers a fruitful field for those interested in the hydrology of California.

Orographic influence--The storm of December, 1937, covered approximately 109,000 square miles, embracing most of California north of Tehachapi Pass, but in only 16,400 square miles or about 15 per cent of the area did the flood-runoff exceed four inches. The runoff from the Ohio River flood of January to February, 1937, averaged the amazing total of 8.9 inches from 204,000 square miles. In terms of total volumes carried by any one river-system, your floods might be considered almost insignificant in comparison with major flood-events in the East. For example, in over half the area covered by the storm of December, 1937, the runoff was less than one-half inch. The principal reasons for this condition are, of course, the high retentive capacity at the beginning of the rainy season and that the areas of high rainfall were limited to the westerly faces of the Coast Range and the Sierras where the orographic influences were effective. These two ranges quite effectively limit the magnitude and the areal extent of the flood-producing rainfall in the State. I think we may assume that the floor of the central valley will seldom contribute significant amounts of flood-runoff on an areal basis: First, the valley is in the rain-shadow of the Coast Range; and secondly, at the beginning of each rainy season its absorptive capacity probably exceeds ten inches or more. Likewise a smaller area, but one which generally is non-contributing, is the higher parts of the Sierras above about 9,000 feet where temperatures are generally in the winter season such that most of the precipitation occurs as snow. However, during the storm of December, 1937, there is evidence that it may have rained to an altitude of 11,000 feet. Whether or not existing flood-records in these high areas give a measure of probable maximum flood-potentialities is not known.

Temperature as related to runoff--The important effect of temperature in relation to ground storage-capacities has already been mentioned. Another very significant feature relates to temperature in controlling the character of precipitation, that is, whether it falls as snow or as rain. For every 1,000-foot rise in altitude along the western front of the Sierras, there is a decrease of about 2° in temperature. Slopes along the western front of the Sierras are such that the area between the several pairs of 1,000-foot contours average about 3,600 square miles up to an altitude of about 7,000 feet and 1,200 square miles between 1,000-foot contours above 7,000 feet. Thus, at critical temperatures a change of only 2° may change the character of the

precipitation from rain to snow or vice versa over more than 3,000 square miles. During the storm of December, 1937, temperatures were from 7° to 8° above normal. Ordinarily a difference in temperature of this magnitude might be considered insignificant, but during that storm such a variation from normal may have resulted in rain instead of snow over an area of from 10,000 to 12,000 square miles, or an area roughly equal to 40 per cent of the effective contributing area of the western slope of the Sierras. It appears that in our flood-problems temperature-effect as well as precipitation must be considered, first in its effect on rainfall, and second as a principal factor in determining availability of natural storage-capacity.

In considering the flood-potentialities of the Sierras, full account must be taken of the peculiar conditions affecting rainfall-characteristics. The storm of December, 1937, covered about 109,000 square miles. The areal extent of the runoff was approximately as follows:

Runoff in inches:		Tributary area in square miles:
	Little or none	3,900
	Less than 1/2	56,400
	1/2 to 4	28,300
	4 to 8	16,400
	More than 8	3,800

In studying the problem of maximum probable runoff, consideration should be given especially to the flood-potentialities of the areas in which the flood-runoff of December, 1937, was between four and eight inches with a view to determining whether, by reason of their altitude and topography, these areas may not be subject to storms of greater magnitude. For example, during the 25 years that observations have been made of the Merced River at Pohono Bridge, the maximum runoff during a single flood-event has been less than five inches. This is only one-half or one-third of the flood-volumes of other parts of the country in which rain and melting snow combine to make floods.

I am not at all sure but that long-continued periods of rain associated with high temperature and a critical amount of snow-cover even at altitudes above 11,000 feet may not constitute a distinct flood-hazard. It goes without saying that the flood-producing potentialities of the High Sierras offer a field for an interesting study of snow in relation to flood-runoff.

Flood-characteristics--Until fairly recently the engineer in his study of floods was most generally concerned with the determination of the maximum flood-discharge and its relation to design-problems. In present-day Nation-wide problems relating to the retention and storage of flood-runoff, either before it reaches defined stream-channels or in stream-channels themselves, it is desirable that information be available not only regarding the stage and discharge-peak but also concerning the total volume of flood-runoff, the extent to which it is concentrated with respect to time, and the effect of channel-storage thereon. During the flood of December, 1937, there were approximately 250 gaging-stations in the area covered being maintained by the Geological Survey in cooperation with the California Department of Public Works, United States Engineer Department, and other agencies, at which continuous records of stage and discharge were obtained. The observations at all of these stations furnish an indication of the total flood-runoff. In the drainage-basins of about 170 stations, however, there is artificial regulation to such an extent that flood-characteristics except as related to total runoff cannot be determined accurately. For 81 widely separated basins, however, complete analyses can be made.

With regard to the total flood-runoff during the flood of December, 1937, four broad areal classifications may be made. The first relates, naturally, to the area of heavy precipitation associated with record-breaking floods. Drainage-basins in which the direct runoff exceeded eight inches include: Bucks Creek, Grizzly Creek, and West Branch in Feather River Basin; South Fork of Yuba River and Canyon Creek; Uvas Creek in Pajaro River Basin; upper Putah Creek, and Eel River; two areas in Tuolumne River Basin; the North Fork of Mokelumne River, and Bear River in the Mokelumne River Basin; Silver Lake in the headwaters of the American River; and probably parts of Russian and Smith rivers where the data are meager. It seems very evident that in these basins the water available for runoff exceeded the capacity of the basins to retain or absorb water by an amount sufficient to produce flood-runoff comparable with the runoff during great floods in the eastern United States.

The second broad areal classification relates to areas where the storm rainfall and runoff were relatively low and yet the momentary peak-discharges reached on December 10 or 11 had not been equaled or exceeded during the period of record. These areas include: Pit River above the three gaging-stations at Fall River Mills, Pit No. 4 Dam, and Ydalpom; and Hat Creek, a tributary of the Pit. By comparison with the floods of other regions neither the total runoff nor the momentary peak-discharge during 1937 can be considered as either a large or medium flood. How-

ever, on the basis of the flood-history of these streams, the records of December, 1937, are a measure of large floods in these particular basins.

The third group includes basins in which the storm-precipitation was greater than took place in many basins where major floods occurred, no snow was involved, yet by reason of a high retentive and absorptive capacity, the flood-runoff was relatively small. In the following basins the storm-precipitation was ten inches or more but the total direct runoff generally was less than three inches: San Lorenzo River on the Coast, Guadalupe, Campbell, and Stevens creeks; Fresno River, Arroyo Seco in the Salinas Basin; South Fork of Mokelumne River; Plum and Alder creeks in South Fork of American River Basin. Brief analysis seems to indicate that the large residuals shown for many of these basins during December, 1937, do not necessarily reflect a high absorptive capacity during all storms. In other words, in basins having such large retentive capacities, it requires studies of many large storms to determine what the range in absorptive capacity may be under varied conditions of antecedent rainfall.

The fourth areal group includes the headwater-basins in the Sierras where by reason of high altitude and low temperature some or all of the precipitation fell as snow that would not materially contribute to the flood-runoff and also those basins in which there was snow on the ground at the beginning of the storm-period that would not melt materially but perhaps actually retained some of the rainfall.

Although I have indicated that on a wide-spread areal basis, volumes of flood-runoff in California are considerably less than those of many drainage-basins in the East, the California floods are generally more concentrated with respect to time. This phenomenon no doubt relates to the limited capacities of the steep channels both for flow and storage in the many small basins making up the major stream-systems. At ten of the 81 gaged streams at which natural flow-conditions obtained, more than 70 per cent of the total flood ran off in 24 hours; at 11 stations, between 60 and 69 per cent; at 33 stations, between 50 and 59 per cent; at 14 stations, between 40 and 49 per cent; and at only 12 stations was the runoff during a 24-hour period less than 40 per cent of the total.

The basins having the greatest degree of concentration are located in the semi-arid and lower foothill-areas where stream-flow is not well sustained and flood-runoff takes place following periods of high intensity as a sudden or flashy peak of relatively small volume with a high maximum instantaneous rate. Such basins include Orestimba, Los Gatos near Coalinga, Woods, Fine Gold, Cottonwood, Big Sandy, Bear Creek near Planada, and Mariposa creeks, and Salinas River above Santa Margarita. Those that drain the upper foothill-area including the Fresno, Chowchilla, Lower Kings, Middle Tuolumne, and others had concentration-ratios of between 60 and 69 per cent. The largest group includes the basins located mainly on the higher slopes of the Sierra Nevada where between 50 and 59 per cent of the runoff occurred during a 24-hour period. In the area studied, most of the basins with natural flow-conditions are small in area and generally with steep slopes and have relatively little capacity for channel-storage. Flood-runoff appeared at the nearest gaging-station soon after the period of maximum rainfall, and crest-stages occurred almost simultaneously over the individual basins. This is, of course, in contrast to the main San Joaquin and Sacramento rivers where wide channels and overflow-areas provide storage-capacities which retard and reduce the flood-crest.

Considering the wide variety of soil, vegetative cover, geology, altitude, slope, and size of the 81 basins studied, there was quite a remarkable coincidence in the time of occurrence of the momentary flood-peaks. In 68 basins the momentary peaks occurred on December 11 and were about equally divided between morning and afternoon. During the late afternoon and evening on December 10 flood-stages occurred in the northern part of the Sacramento River Drainage-Basin. During the morning of December 11 there were peak-stages throughout the northern Sierra Nevada and areas near San Francisco Bay. In the southern Sierra Nevada, in general the peak-stages were reached during the afternoon and evening of December 11. At many of the stations there were two peaks, but generally the second reached the higher stage. The time of occurrence of the maximum peaks are so nearly simultaneous that no correlation with basin-characteristics has been attempted. In fact, such differences in times of crest as existed were largely related to the timing of the rainfall.

Considering the conditions peculiar to California, I suppose that no one but a rank outsider would have undertaken to determine rainfall-relations throughout the 100,000 square miles covered by the storm of December, 1937. Fools, however, rush in where angels fear to tread. Meager as much of the basic information was, and generalized as the conclusions may be, I make the point that they must add something to our fund of hydrologic information and that they are surely a necessary adjunct to all experimental research designed to establish rainfall-runoff-

soil relationships. This is especially true in much of the West where the conditions are so varied and complex as to make difficult the translation of spot-values into areal volumes. The conclusions are as significant perhaps as would be obtained by applying the rainfall-runoff relations determined at typical experimental areas, such as the North Fork Station, to the drainage-basin of the upper Pit or to drainage-basins in the coastal areas south of San Francisco. I believe that each type of research has an important place in the broad field of scientific and applied hydrology. The generalized results of the large basin-wide studies disclose tendencies, the exact mechanics of which may be examined through intensive studies in small areas. On the other hand, until the results of the experiments on small areas are correlated with conditions on major drainage-basins, their contribution in major present-day hydrologic problems, which are necessarily basin-wide in scope, may be more theoretical than practical. Studies to perfect such correlations are now under way.

Nearly all that is written herein, and much more, is included in United States Geological Survey Water-Supply Paper 843 of which Mr. Briggs, who collaborated with me in preparation of this brief discussion, is co-author with Mr. McGlashan.

U. S. Geological Survey,
Washington, D. C.

REPORT TO F. J. VEIHMEYER, CHAIRMAN OF SOUTH PACIFIC COMMITTEE, ON THE MEETING OF SOUTH PACIFIC AREA OF SECTION OF HYDROLOGY OF THE AMERICAN GEOPHYSICAL UNION IN SACRAMENTO, CALIFORNIA, JANUARY 16-18, 1941

Harold Conkling, Chairman

The Meeting was held in the Little Theatre of the Memorial Auditorium at Sacramento. This was furnished by the Sacramento Convention Bureau, which also furnished badges in which names could be inserted and a clerk to help with registration. Fred Sprague of the Pacific Gas and Electric Company furnished a lantern and showed the slides which the various authors of papers had prepared.

Leupold, Volpel and Company through the good offices of J. C. Stevens exhibited one of the Stevens snow-measuring apparatus and two types of Stevens water-stage recorders. Considerable trouble and expense was incurred in doing this as Robert Stevens brought them down by truck from Portland and was available at all times for explanation. Otto H. Meyer, who also delivered a paper on the morning of January 17, exhibited a "flood-routing" apparatus of his own design and construction. By this device with the hydrograph of a flood on any tributary, the hydrograph of the same flood at some lower point is readily attainable.

Although rain threatened most of the time none occurred during the three days, making it possible to take the trips which had been planned. The fact that the River was high and the spillway and by-pass features of the Sacramento River Flood-Control Project were functioning added to the interest of the trip over it. At the same time the streams were not so high as to block transportation in the Valley as is the case in larger floods. Except for minor changes due to water on the roads the trip was taken as laid out by Martin H. Blote of the State Division of Water Resources, who prepared an excellent circular describing the points of interest along the itinerary together with maps. The trip to Shasta Dam was made especially enjoyable by the many courtesies of Ralph Lowry, Construction Engineer of the United States Bureau of Reclamation, and of Frank Crowe, General Superintendent for the contractors, Pacific Construction Company.

Registration--Total registration was 206. This is classified in several ways as follows:

Subdivision by States: California, 189; Nevada, 10; Colorado, 2; Idaho, 2; Oregon, 2; Washington, 1; or in total 206.

Subdivision by employment: Federal, 75; State, 43; universities, 26; irrigation-district directors, managers, and engineers, 23; consulting engineers, 11; utilities, 11; city, 10; miscellaneous, 4; county, 3; or in total 206.

Subdivision by sections of California (California registrations only): Sacramento Valley, 107; San Francisco Bay Area and Coastal Valleys to the south, 44; San Joaquin Valley, 22; Southern California (south of Tehachapi Mountains), 16; or in total 189.

Attendance: January 16--Morning session, 157; afternoon session, 157. January 17--Morning session, 152; afternoon, trip over Sacramento Basin and Flood-Control Project, 54. January 18--Trip to Shasta Dam, 29.

Western Interstate Snow-Survey Conference--The Snow-Survey Conference was under the chairmanship of Fred Paget. It was a dinner meeting which also included papers and discussions on snow-surveying and the business of the organization. The attendance was 92.

Luncheon--Ten members of the Committee of the South Pacific Area met at lunch January 16 at the Sutter Club and discussed the next meeting. The consensus of opinion was that the invitation of Franklin Thomas should be accepted and the meeting held at California Institute of Technology. No definite decision was reached and the matter was left in the hands of Chairman Veihmeyer.

The program--For various reasons the chairman of each session of the Section of Hydrology, American Geophysical Union, whose names are given in the printed program, were unable to attend. Fortunately the following graciously consented to serve: Morning of January 16, M. P. O'Brien, Chairman, Department of Mechanical Engineering, University of California, Berkeley, California; afternoon of January 16, S. B. Morris, Dean, School of Engineering, Stanford University, California; morning of January 17, Albert Givan, Chief Engineer, Sacramento Municipal Utility District, Sacramento, California.

The papers presented were of a high order and aroused much interest. It is evident that either another half-day should have been devoted to the meetings proper in order to allow more time for discussion or that fewer papers should have been listed and the same purpose thus accomplished. The former plan would have sacrificed the trip to Shasta Dam and the latter would have sacrificed some interesting papers.

Chairman Phil E. Church of the University of Washington was requested to report for the Committee on Use of the Median Versus Arithmetical Average, appointed at the Seattle meeting in 1940 of the North Pacific Area, Section of Hydrology. This he did briefly and it is published in this volume (Part I, Transactions of 1941 of the American Geophysical Union), together with the papers delivered at the Sacramento Meeting.

J. Bjerknes was not able to attend because of illness and his very technical paper was ably abstracted and presented by Joseph B. Paulson, Jr., of the United States Engineer Corps at Sacramento, who also presented his own paper the following morning. W. G. Hoyt's paper was presented by R. C. Briggs of the San Francisco office of the United States Geological Survey, who aided in its preparation.

Conclusion--In conclusion, grateful appreciation is expressed for the help of practically all the members of the Committee for the South Pacific Area, not only in aiding with suggestions for the program but in making the meeting a success.

DISCUSSION--Continued from page 111

Mr. Kraebel stated that as a measure of first aid to newly burned watersheds, the Forest Service has developed a method of sowing a cover-crop of common mustard immediately after the fire. This gives protection to the inter-shrub soil-surfaces, retards runoff and erosion and increases infiltration. In easily accessible areas the sowing is usually done by hand at the rate of five or six pounds of seed per acre. In inaccessible areas or where speed is essential the sowing is done by airplane. Under optimum conditions such sowing has produced a cover averaging about six plants to the square foot. By collecting and weighing samples of the mustard cover grown on treated areas, it has been found that yields as great as 2-1/2 tons per acre (dry weight of pulled plants) had been produced the first season after sowing. The dead plants break down to form an effective mulch on the soil-surface. Volunteer crops continue during the following three years but by the fifth and sixth years the mustard yields to the recovering chaparral.

To date about 65,000 to 70,000 acres of burned chaparral-areas have been treated at a cost of about $1.25 per acre. While this method of obtaining a vegetation-cover after denudation by fire has proven very successful in the chaparral-type of southern California, its usefulness in the brush- and forest-types of the Sierra Nevada is yet to be determined.

AMERICAN GEOPHYSICAL UNION

REGIONAL MEETING

SOUTH PACIFIC COAST AREA

January 16-18, 1941

PART I-B

WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

REPORTS AND PAPERS

Sacramento, California

January 16, 1941

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Dinner session, January 16, 1941
William A. Lang, presiding

DINNER SESSION

William A. Lang, presiding

COLOR FILM ON SNOW-SURVEYING IN THE CENTRAL SIERRA NEVADA

Walter Herz

This color-film was thoroughly enjoyed by all present as at Seattle. It has now been expanded by the addition--made possible by the trip to the Pacific Northwest last summer--of a film on Crater Lake, Mount Hood, Mount Baker, and the Washington-Oregon ocean surf.

Sierra Pacific Power Company,
Reno, Nevada

IN MEMORIAM: JAMES E. PHILLIPS

George A. Lewis

Let all present pause a few minutes in respect for the memory of one of our associates in the work that has occasioned this gathering.

JAMES EMERSON PHILLIPS was born July 8, 1883, in Russellville, Indiana. After graduating from Friends Academy at Bloomingdale, he matriculated at Wabash College in Crawfordsville. After two years he decided to take up engineering and enrolled at Rose Polytechnic Institute at Terre Haute. At the end of his junior year he was a candidate for the office of Surveyor of Parke County, and upon election withdrew from school. When his term of office as County Surveyor expired he did not run for reelection, but removed to Portland, Oregon, where he engaged in private engineering practice until 1912.

His residence in Los Angeles began in 1912, and his first employment by the Department of Water and Power, in that year, was as a draughtsman in the Bureau of Water Works and Supply. He advanced to the position of chief draughtsman in 1919. In 1924 he was appointed Assistant Civil Engineer in charge of office and field engineering. Four years later he was placed in charge of maintenance and operation of the Los Angeles Aqueduct and all its facilities. In 1938 he was given the final promotion of Civil Engineer, the position held at the time of his death on October 26, 1940.

His membership in National Engineering Societies, and his work in connection therewith, gave him a wide acquaintanceship that sorrows at his death and sympathizes with his widow and three sons.

Los Angeles Department of Water and Power,
Los Angeles, California

WHITHER SNOW-SURVEYS?

Harold Conkling

Mr. Chairman, and fellow members of the Western Interstate Snow-Survey Conference: It is a source of great pleasure to all of us Sacramento snow-surveyors that this year's meeting is being held in Sacramento. This city itself has always been more or less snow conscious because of the American River Watershed in our own backyard and the recurring high water in the rivers at our doorstep.

The State Engineer's office here cooperated with Dr. Church on his early work as far back as 1917. Our present program extends back ten years, beginning in 1929 when under my direction, Harlowe Stafford, assisted by Spencer Munson, laid out a network of snow-courses embracing the Sierra. Fred Paget has been looking after the details for the past five years, taking up where Harlowe left off.

Our forecasting results in California have been on the whole satisfactory, but there are some areas where we are still feeling our way, and for some time I have had it in mind to make an investigation of all the results secured in all the watersheds, should an opportunity occur to do so. To date the opportunity has not occurred.

This meeting tonight would seem to be an appropriate occasion to introduce this subject, not in its restricted phase as it affects California itself, but rather in its broad phase as affecting all the States of the West, and I would like to take a few moments of your time to speak of this.

The introduction of snow-survey methods and the adoption of snow-survey programs proceeds space. To Dr. Church, of course, goes all the credit for developing and introducing the science of snow-surveying. Due to the success of his efforts, the Nevada Cooperative Snow-Surveys was organized and Nevada was the first State to adopt and benefit from an organized snow-survey program. In 1935 the Department of Agriculture, acting through the Division of Irrigation of the Bureau of Agricultural Engineering, began the organization of cooperative snow-surveys in the rest of the Western States. The western provinces of Canada likewise followed suit, so that today there is a comprehensive snow-survey program in all of the American States and Canadian Provinces west of the Great Plains.

Recent enthusiasm for this work has appeared in the East. In September 1940, at a meeting held at Cambridge, Massachusetts, the Eastern Snow Conference was organized, and just a little over a month ago the Great Lakes Snow Conference came into being at a meeting held at Detroit, Michigan.

Conditions in the East, of course, are different from conditions in the West, but snow is snow wherever you find it, and in developing their snow-survey programs our eastern cousins will probably follow our lead and adopt our methods to a great degree.

This would seem a further incentive for us to make an inventory. We have been at the game for quite a while now and on many of the western watersheds accurate forecasts are made every year. In California and Nevada the results on the whole are satisfactory. However, every once in a while an unusual year occurs and the results are not so close, and there are a few watersheds where a normally dependable correlation between snow-pack as measured and the ensuing runoff has not as yet been established in spite of our years of effort. Why is this?

The factors influencing the efficiency of runoff from the snow-fields are many and varied. Our <u>analytical</u> knowledge of how they might act is sound, but <u>true</u> knowledge of how they actually do act is lacking. More experimental work is needed to determine the effect of these various factors as they act in the field and to find out whether the effect can be anticipated.

Along this same line it would also seem to me that an appraisal should be made and an accounting rendered of the value of the work done to date in all the watersheds of the Western States. Nevada has records covering over a quarter of a century, Utah 18 years, California has complete records for the past decade, and most of the other Western States have records for at least five years.

An investigation of this sort to be successful would have to consider all pertinent data from all quarters of the Western States. There would probably be no hesitation on the part of any organization in supplying for research all available data. I believe all would welcome the opportunity. We would like to make this investigation here in California, but our State funds are meager and have to be spread thin over our large territory to accomplish the practical results that we are getting today.

As the outcome of such research we should find the answer to some of the problems that vex us today. It may be found that in all watersheds correct forecasts can be made if the effect of such modifying factors that can be measured are evaluated. On the other hand, it may be found that in some watersheds, because of the nature of things, no dependable practical answer can ever be expected without an expenditure of money beyond that economically feasible.

Regardless of the outcome it would seem that such an investigation should be made and it is only fitting that it should have its inception in our own snow-survey organization, the Western Interstate Snow-Survey Conference.

Division of Water Resources,
California Department of Public Works,
Sacramento, California

DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--Mr. Conkling's retrospect and prospect for snow-surveying brings up the days when surveying was sporadic and represented individual rather than public initiative. This formative and uncertain period deserves recording before it fades away in the greater enterprise that has developed from it. The main series from the beginning to the present is as follows:

Charles E. Mixer, Chief Engineer, Rumford Falls Power Company, assisted by United States Weather Bureau and United States Geological Survey, Androscoggin Basin, Maine.	1900
Dr. Robert E. Horton (United States Geological Survey), Utica, New York	1903
Dr. J. E. Church, Meteorologist, Nevada Agricultural Experiment Station (Mount Rose snow-sampler, 1909)	1910
Union Water Power Company (Rangeley Storage Area, Androscoggin River Basin), Lewiston, Maine.	1911
J. Cecil Alter, United States Weather Bureau, Salt Lake City, Utah.	1911
Engineering Department, Salt Lake City (Big Cottonwood Canyon).	1914
Zurich Glacier Commission, Zurich, Switzerland.	1914
Canadian Meteorological Service (Bow River Basin, Alberta).	1916
California State Engineer	1917
Nevada Cooperative Snow-Surveys	1919
United States Reclamation Service (Jackson Lake, Wyoming)	1919
Washington Water Power Company, Spokane (Coeur d'Alene Basin and later Lake Chelan) . . .	1920
International St. Marys River Basin, Montana-Alberta (United States Geological Survey and Dominion Power and Hydrometric Bureau)	1922
Utah Cooperative Snow-Surveys	1923
Black River Regulating District, New York	1925
New York Cooperative Snow-Surveys	1925
Los Angeles Department of Water and Power, Owens Basin.	1925
Newfoundland.	1926
Oregon Cooperative Snow-Surveys	1928
Shawinigan Power Company, St. Maries Basin, Quebec.	1928
California Cooperative Snow-Surveys	1929
Victoria State Electrical Commission, Australia	1930
Upper Missouri River Basin, Fort Peck Reservoir (United States Army Engineers and United States Geological Survey).	1934
British Columbia, Water Rights Branch	1935
Federal-State Cooperative Snow-Surveys (Division of Irrigation, United States Bureau of Agricultural Engineering).	1935
Public Service Company of New Hampshire (Merrimack River Basin), Concord, New Hampshire, and United States Weather Bureau	1938

The order of State and provincial organizations is approximately as follows: California (informal) 1917-1923; Nevada 1919; Utah 1923; New York 1925; Oregon 1928; California (formal) 1929; British Columbia 1935; Federal-State (Western States) 1935.

California's cooperation in 1917 should not be counted a false start. Not only did Paul M. Norboe, at that time Chief Assistant State Engineer, dream of forecasting water-supplies but actually persuated the Legislature to pass acts permitting him to investigate its possibility. He then learned about the Nevada snow-studies and had a major part in organizing the Nevada Cooperative Snow-Surveys and sustaining them. Through mutual assistance at critical times there was no lapse in the records of either State.

The compiling of all the organizations and leaders in snow-surveying would be a worthy project at this time. They are pioneers and inseparable from any history of the work.

Continuous snow-surveys have been made in the Truckee-Tahoe Basin, Nevada-California, since 1910 and in the Androscoggin Basin since 1911. There has been little interruption in Big Cottonwood Canyon, Utah, since 1914. In the South Yuba Basin, California, and at Jackson Lake, Wyoming, the record has been continuous since 1919. Thus the oldest records span 20 to 30 years--a period now ripe for study.

ROUND-TABLE REPORT ON ACCURACY OF STREAM-FLOW FORECASTS FOR 1940

CALIFORNIA COOPERATIVE SNOW-SURVEYS: RESULTS OF 1940 FORECASTS

Fred Paget

Of the 1940 California forecasts, on the whole they were fair. For the 11 watersheds covered by the published forecasts, five of them were good with a difference between forecast and actual of from three to ten per cent; four of them were fair with differences of between ten and 20 per cent, while two were poor with discrepancies over 20 per cent.

For some reason the 1939-40 winter weather did not at all conform to normal behavior. The cyclonic storms that bring California's winter precipitation forsook their usual chilly path from the Aleutian Islands across the Gulf of Alaska to the mainland and instead followed a warmer route southerly to the Hawaiian Islands and then swung inland from there. These warmer storms from the tropical seas brought rain to elevations that usually receive only snow during the winter months.

Total winter precipitation was well above normal and at the higher elevations this was reflected in the heavy snow-pack. The snow-pack, however, did not cover its usual area as the warm rains kept the lower fringe of the snow-pack fully 1,000 feet higher than its ordinary location. Below the unusually high snow-line these same warm rains filled the ground-water storage of the bare watershed to overflowing.

A severe storm during the time of the final snow-surveys were being made somewhat complicated the office work as many measurements made before and during the storm had to be corrected to include the effect of the storm. From the adjusted figures forecasts of runoff were made and in publishing these figures a segregation was made between the storm-runoff due to the late March rain and the expected runoff due to snow-melt as indicated by the snow-pack measurements.

Of all the forecasts--five good, four fair, and two poor--all were low. The runoff in every case exceeded the forecast. Four of the good forecasts occurred in the block of watersheds beginning with the Tuolumne on the north and running south through the Merced and the Upper San Joaquin to the Kings. The two southernmost watersheds were the poor ones. The Kaweah having a 22 per cent discrepancy and the Kern a 33 per cent divergence. Of the four northern watersheds on which forecasts were published, the Yuba just got under the wire as a good one with ten per cent discrepancy while the three othere were fair, the Mokelumne with 17 per cent, the American with 20 per cent, and the Feather with 17 per cent difference between forecast and actual.

The fact that the forecasts were all low would point to the probability that the reducing effect of the lack of low snow was overestimated and the increasing effect of the complete saturation of the low areas was underestimated.

In the four central watersheds the combined effect of these two misjudged factors was not great enough to produce a discrepancy of over ten per cent. In the northern watersheds where the forecasts were only fair the effect of these two factors was aggravated due to the larger proportional amount of moderately elevated areas usually snow-covered but this year bare.

In the two watersheds at the south end of the Sierra, where the forecasts were poor, no snow-courses are maintained in the higher areas of the watersheds because of the remote and inaccessible nature of the country. With the past season's unusual distribution of snowfall it is probable that these high areas may have had an unusual richness of snow-pack. The effect of the higher runoff from these unmeasured areas combined with the imperfect adjustments for lack of low snow and surcharged water-table could well account for the greater errors experienced in these two watersheds.

Because of last winter's experience we now feel that as time goes on we may be better able to evaluate the factors influencing runoff and we are heartened by the fact that in spite of unusual conditions all the 1940 forecasts were on the conservative side and with the exception of the two south watersheds were within a practical degree of accuracy.

Division of Water Resources,
California Department of Public Works,
Sacramento, California

SUMMARY OF 1940 FORECAST FOR OWENS RIVER DRAINAGE-BASIN

James E. Jones

The plan to summarize each year the results of the forecast made for the several regions represented in the Snow-Survey Conference permits the continuance of discussions from time to time of unsettled points of interest.

For the eastern slope of the Sierra Nevada draining into the Owens Basin, Table 1 affords the comparison of the estimated runoff based on the snow-surveys of late March and early April, 1940, with the actual.

Table 1--Comparison of 1939-40 estimate with actual discharge

Region	Hydrographic-year estimate		36-year mean, sec.-ft.	Actual runoff	
	Per cent	Sec.-ft.		Sec.-ft.	Per cent of estimate
Owens River, Round Valley	96	211	220	209	99
Rock Creek, Little Round Valley	99	36.3	36.7	35.0	96
Bishop Creek, Plant No. 6 - Natural	102	92.7	90.9	84.7	91
Big Pine Creek, USGS	72	28.4	39.2	31.4	110
Cottonwood Creek, USGS	58	16.2	27.8	20.4	126

Note: Bishop Creek estimated on 30-year record.

The methods used were the same as mentioned at the Snow-Survey Conference held at Stanford University, January 12, 1940, and the statement made in the 1940 Transactions of the American Geophysical Union, that no single method appears to be good for all conditions that arise, is still correct.

The data obtained in the 1940 snow-surveys indicated a year subnormal in most localities, but with Bishop Creek slightly above normal, and the catch falling off in both the northerly and southerly directions. The column headed "Per cent" in Table 1 reflects the estimated ratio of each stream to a normal year, and the great variation between Bishop and Cottonwood creeks is noteworthy. The distance between the two creeks is about 70 miles, Bishop being the northern one.

The effects of the unmeasured precipitation upon the high elevations of the Sierra Nevada, the percolation into the terrain and its return to surface-flow, the loss by evaporation, all are matters of great interest to the forecaster, and each, in several forms, has been used to explain the divergence between forecast and actual runoff.

Bureau of Water Works and Supply of the City of Los Angeles,
Los Angeles, California

SUMMARY OF 1940 FORECAST FOR HUNTINGTON, FLORENCE, AND SHAVER LAKES

W. A. Lang

The Edison Company's Big Creek hydroelectric development is served by three storage-reservoirs, namely, Huntington, Florence, and Shaver lakes, having a combined capacity of 288,523 acre-feet. These three reservoirs impound the runoff of Bear Creek, Mono Creek, South Fork San Joaquin River, Big Creek, Pitman Creek, and Stevenson Creek. The combined area of the six drainage-basins is 450 square miles, 45 per cent of which is above an elevation of 10,000 feet.

Forecasts based on snow-survey data are made at monthly intervals beginning March 1, and, when heavy storms or operating requirements make it desirable, semi-monthly forecasts are made. In general, all forecasts are based primarily on the results of snow-surveys made at two key courses, namely, Huntington Lake, elevation 7,000 feet, and Kaiser Pass, elevation 9,200 feet. However, consideration is given to data from 17 other snow-courses in the San Joaquin River Basin. When sufficient data have been collected from some additional courses recently established by the Company, all data from the several available sources will be correlated and new curves prepared.

We have obtained very satisfactory results using the direct method of forecasting. Three curves are used which give the expected runoff for the periods November to July, March to July, and April to July, all based on the water-content as of April 1 snow-survey data. When making forecasts before April 1, normal precipitation for the interim is added to the snow-survey data used. Likewise, when using the curve for November to July for checking our forecasts, the runoff received between November 1 and the date of the prediction is deducted.

Using the above-mentioned methods, we forecasted a runoff of 585,000 acre-feet on March 1, 1940, and 620,000 acre-feet on April 1, 1940. The actual runoff received was 614,600 acre-feet, indicating an error of -4.8 per cent as of March 1 and +0.9 per cent as of April 1 for our 1940 forecasts.

Southern California Edison Company, Ltd.,
Los Angeles, California

RUNOFF FROM MELTING SNOW ON THE MOKELUMNE WATERSHED, 1940

L. Standish Hall

The runoff for the period April to July, inclusive, in the Mokelumne River as the result of melting snow at the high altitudes showed a large deviation between the measured runoff and the estimate prepared as the result of snow-surveys taken on April 1.

The preparation of the estimate of the runoff from melting snow during the past season was complicated by the fact that a very heavy storm occurred during the last three days of March, subsequent to the measurement of many of the snow-courses. Furthermore, the fact that there was no snow on the ground below the 6,000-foot elevation possibly affected the subsequent runoff, due to the smaller area covered by the snow-field and the consequent lower evaporation- and transpiration-losses.

The water-content of the snow on April 1 was originally estimated as 444,000 acre-feet, based on the actual measurements, but an examination of the records showed that at the stations at Carson Pass, Wheeler Lake, Pacific Valley, Lake Alpine, and Silver Lake, the observations of the water-content of the snow were taken prior to the heavy storm occurring the last three days of the month. By comparison with the records of previous years, the records at these five stations were increased, with the result that the total water-content of the snow on the watershed on April 1 was estimated to have been 495,000 acre-feet. The actual natural runoff of the Mokelumne River during the melting-snow period, after correcting for storage in the Pacific Gas and Electric Company Salt Springs Reservoir, was 497,000 acre-feet. Hence, even with the corrected figure of the water-content of the snow, the subsequent runoff was slightly in excess of the total estimated available water on the watershed.

Precipitation on the upper watershed during the month of April was 1.09 inches, but for the purpose of estimating the snow-runoff, the precipitation of 1.60 inches which occurred on March 31 was included with the April precipitation, making the total precipitation for the three months from April to June, inclusive, 3.88 inches, as compared with a normal of 5.8 inches. With this deficient precipitation during the snow-melt period, the total runoff from April to July should have been reduced to 75 per cent of the water-content of the snow on April 1, or to approximately 370,000 acre-feet. The actual runoff was nearly 500,000 acre-feet, or 130,000 acre-feet in excess of the estimated quantity. For the purpose of checking the discrepancy, an estimate was made of the runoff of snow, based on measurements taken on May 1. On this date only four stations were observed, but by determining the relative melting of the snow since the observations on April 1 an estimate of the probable water-content of the snow on May 1 was arrived at. This was determined to be 323,000 acre-feet, and applying a coefficient of 75 per cent to estimate the probable runoff, 242,000 acre-feet should have passed the gaging station near Mokelumne Hill during the months of May to July, inclusive. Actually the runoff for these three months was 336,000 acre-feet, or 94,000 acre-feet in excess of the estimated runoff for this period. The fact that this discrepancy practically coincides with the discrepancy between the total runoff for the period from April to July, inclusive, would perhaps indicate that the water-content of the snow on the watershed was in excess of the amount actually measured at the snow-courses.

However, if the estimate of runoff from melting snow is based on the water-content of the stations above 7,000-foot elevation, it is found that the runoff for the year 1940 agrees quite

closely with the results obtained in previous years. It is difficult to give an adequate explanation of the inconsistency between the actual and estimated runoff for the year 1940. It is believed that the fact that in most previous years when there has been an equivalent snow-pack at the higher altitudes there has been snow on the ground between the 4,000- and 6,000-foot levels on April 1, whereas in the past year there was snow on the ground only above the 6,000-foot level, might have some bearing on the departure during this season from the previous runoff-expectancy.

The conclusions to be drawn are: (1) That the water-content of the snow at the stations measured was not representative of the mean water-content of the entire watershed, due to unusual differential melting of the snow-pack or possibly to unusual drifting of snow; (2) that the snow on the ground below the 6,000-foot elevation is not as effective in producing runoff as that at higher elevations, due to greater losses from (a) infiltration of water into thicker soils during the melting period, or (b) greater transpiration-losses, due to heavier vegetative cover in the 4,000-foot to 6,000-foot zone. It is possible that the actual truths may lie in a combination of both of these factors, but it will be necessary to wait until the occurrence of another season with a similar distribution of the snow-pack before a verification of the above hypothesis is possible.

East Bay Municipal Utility District,
Oakland, California

NEVADA COOPERATIVE SNOW-SURVEYS--EASTERN SLOPE, CENTRAL SIERRA NEVADA: COMPARISON OF FORECAST AND ACTUAL RESULTS, 1940

H. P. Boardman, George G. Devore, and Leigh Sanford, Forecast Committee

Table 1 shows the comparison of forecasts and actual results for the streams flowing into Nevada from the eastern slopes of the Sierra Nevada.

Table 1

Basin	Normals Amount	Forecast		Actual results		Difference	
		Amount	per cent normal	per cent normal	Amount	Amount	per cent normal
	feet	feet			feet	feet	
Tahoe, April 1 to highwater rise	1.68	1.38	82.2	95.2	1.60	0.22	13.0
	ac-ft	ac-ft			ac-ft	ac-ft	
Truckee (exclusive of Tahoe) runoff, April to July	325,700	245,000	75.2	93.5	304,400	59,400	18.3
Carson, at Ft. Churchill	230,000	185,000	80.4	80.1	184,230	770	0.3
West Walker, above Coleville	191,200	153,000	80.0	84.9	162,420	9,420	4.9
East Walker, at Bridgeport Dam	73,000	52,000	71.2	76.3	55,730	3,730	5.1

Discussion

Truckee River--In looking for an explanation of the excess of Truckee River runoff (exclusive of Tahoe) above the forecast for April-July, 1940, a study was made of the precipitation-records of six stations, namely, Tahoe, Truckee, Soda Springs, Bowman Dam, Blue Canyon, and Lake Spaulding.

September and October, 1939, were well above normal while November and December were deficient. September to November combined were from 94 to 141 per cent of normal for Soda Springs, Tahoe, and Truckee but only 62 to 70 per cent of normal for the other three stations.

We generally use December to March, inclusive, as the period of winter precipitation when, in the central Sierra region, most of the precipitation is in the form of snow above altitude 6,000 feet. Last winter there was considerable rain in January above altitude 7,000 feet and some as high as 8,000 feet. Also there was much rain in the last week of March. I was surprised

to find that, in spite of the deficiency of precipitation in December, the total for December to March was from 158 per cent of normal for Tahoe to 179 per cent of normal for Soda Springs, the other four stations ranging in between these limits. This shows very consistent results for this general region.

Quantitatively the excess above normal ranges from 12 inches for Tahoe and Truckee to more than two feet for each of the other four stations, the maximum excess being 31.3 inches at Lake Spaulding.

The Truckee River runoff was only about 40 per cent of normal in December but was above normal in each of the months January, February, and March, totaling practically 150 per cent of normal or nearly 40,000 acre-feet above normal. The runoff of April to July, 304,400 acre-feet, was 59,400 acre-feet more than the forecast called for in spite of the fact that the precipitation of April to June was deficient at all of the six stations except Truckee.

The combination of the excess runoff of January to March above normal and the excess runoff of April to July above that predicted gives about 99,000 acre-feet. Ignoring the tributary drainage-area in the Carson Range, since it contains no Weather Bureau precipitation-stations in the Truckee Basin, we have tributary about 206 square miles or 132,000 acres above altitude 6,000 feet in the main Sierra range. (The Carson Range is the north and south range east of Tahoe, including Mount Rose and extending from Sierra Valley on the north to Kit Carson Pass on the south.) Nine inches of water over this area would equal the above-mentioned 99,000 acre-feet of excess runoff for the six months January to July.

This nine inches subtracted from the probable excess of precipitation January to March leaves plenty to take care of deficient ground-water due to low precipitation of November to December and also deficient precipitation of April to June.

If the tributary area above altitude 6,000 feet in the Carson Range (141 square miles) is included, then six-inch depth over the main Sierra Range and 4.4-inch depth over the Carson Range would account for the excess runoff of 99,000 acre-feet, or seven inches over the main range and three inches over the Carson Range.

Marlette Lake is about altitude 8,000 feet in the Carson Range but in the Tahoe Basin, 11 miles southeast of the Truckee Basin. At Marlette the precipitation of December to March was 149 per cent of normal and the excess over normal was 9.25 inches.

The April 1 snow-survey showed from 90 to 108 per cent of normal water-content for the high-level courses and 50 to 70 per cent for lower levels. The water which provided the excess runoff of April to July must have been retained in the ground temporarily. If this is not the case where did the excess runoff come from?

I have none too much confidence in the accuracy of quantitative estimates of precipitation on a whole watershed based on Weather Bureau precipitation-measurements at scattered points (with few of them at high elevations) or even based on snow-surveys at numerous locations, because of great differences at about the same elevations, due to varying exposures.

However, in this case there appears to be ample excess precipitation to allow considerable leeway in accounting for excess of runoff over that indicated by the snow-surveys.

The conclusion I draw from this study is that whenever a winter brings considerable rain during the usual months of snowfall, it will be worth while to supplement the snow-survey analysis with an examination of available Weather Bureau winter precipitation-records and if there is a notable excess of precipitation in per cent of normal over the snow-survey, make a quantitative estimate of the excess, also taking into account the winter runoff and its relation to normal.

Tahoe--The forecasted rise of Tahoe was also surpassed by a considerable percentage but in this case the mean of two methods of estimating the rise was 1.48 feet which is one and one-half inches or 7.15 per cent of normal less than actually occurred. The published forecast was the conservative decision of the Committee, evidently too conservative.

Other basins--The Carson and Walker forecasts and actual results were close enough to need no particular explanation. It will be noticed that the East and West Walker both exceeded the forecast by about five per cent of normal.

Reno, Nevada

REVIEW OF THE 1940 FORECASTS OF RUNOFF FOR EASTERN NEVADA

Carl Elges

Region and period	Normal flow, acre-feet	Forecasted flow, acre-feet	Actual flow, acre-feet	Difference per cent of normal
Humboldt River at Palisade (March-July)	250,000	140,000	129,370	4.3[a]
Lamoille Creek at Power House (April-July)	22,800	25,000	24,930	0.3
South Fork, Humboldt River at Bolton Ranch (April-July)	35,000	38,000	40,400	6.9
Martin Creek, Little Humboldt River at United States Gaging Station (March-July)	14,300	15,000	16,516	10.6

[a]Difference for 1938-1939 was 4.6 per cent.

The forecast for the South Fork was based on only three years of record. Extensive studies must be made of the relationship of snow-cover to runoff for the Martin Creek Drainage, since a change in some of the courses has completely altered the old dependable system that was in use. The above forecast is the first one made based upon new relationships.

Nevada Agricultural Experiment Station,
Reno, Nevada

EXPERIENCE WITH IRRIGATION-WATER FORECASTING IN UPPER COLUMBIA DRAINAGE-BASIN DURING 1940

James C. Marr

Our last attempts to forecast water-supplies based on snow-surveys, April 1, 1940, appear to have been fairly successful considering the respective length of the snow-survey record and the unusual weather conditions that prevailed last winter and the preceding fall. Only a few examples can be given, because for most of our streams the runoff has not yet been completed.

Weather conditions made the forecasting more difficult than usual last year, because the fall of 1939 was unusually dry, the winter was abnormally warm and wet, and the snow-covered areas were much smaller than usual. These factors were weighted by considering the dry fall as entirely nullified by the wet winter and by accepting as unaffected by winter melting the snow at the higher elevations only. Without exception our forecasts were low, which indicates that these conditions were weighted at least in the right direction.

We have in Upper Columbia Drainage three snow-survey records that are of sufficient duration to serve properly as the bases for forecasting. The rest of our records are two, three, or four years old, which may be too short a time to establish the true relationship between water-content of snow-cover and runoff. This brevity of record may explain the excessive error of estimate obtained in some instances.

According to preliminary tabulations the accumulated natural flow of Snake River near Moran, Wyoming, during the period March 18, 1940, to September 30, 1940, was 666,900 acre-feet. The amount forecast was 600,000 acre-feet. The error of estimate is ten per cent. The maximum deviation from the straight-line relationship that has been found to exist between water-content of snow-cover and runoff is such as to warrant an error of this order. The snow-survey record in this case is continuous since 1919.

The snow-survey record for Spokane Drainage is also continuous since 1919. The runoff from Spokane River at Spokane, Washington, during the period October 1, 1939, to September 30, 1940, was forecast at 3,500,000 acre-feet and amounted to 3,548,950 acre-feet. The error of estimate is 1.4 per cent. A much greater deviation has occurred, owing, it is believed, to the effects of underground storage.

The third and only other long snow-survey record we have, namely, that for Boise Drainage continuous since 1930, has served for several years as an excellent basis for water-supply

forecasting. The discharge of Boise River at Dowling Ranch corrected for storage in Arrowrock Reservoir plus the discharge of Moore Creek for the period October 1, 1939, to September 30, 1940, amounted closely to 1,605,000 acre-feet (U. S. Geol. Surv. stream-flow record, except flow at Dowling Ranch, which was supplied by Boise Project Board of Control). Last April it was forecast at 1,500,000 acre-feet. The error of estimate amounts to 7.0 per cent. The relationship which has been found between water-content of snow-cover and runoff has remained remarkably consistent throughout the past 11 years and appears to warrant confidence that it may continue to serve as the basis of accurate forecasting.

The following results are based on two-, three-, or four-year snow-survey records: According to preliminary calculations the discharge of Payette River near Horseshoe Bend, Idaho, adjusted for storage in Payette Lake and Deadwood Reservoir and with irrigation-water used by Lake Irrigation District added, amounted to 2,186,500 acre-feet during the year ending September 30, 1940. The forecast was 1,700,000 acre-feet. The error of estimate is 22 per cent.

An attempt to forecast the runoff from Weiser Drainage based on snow-survey results for two years failed completely. The error of estimate amounted to 42 per cent.

On the basis of three-year snow-survey results the discharge of Salmon River at Whitebird, Idaho, for the period October 1, 1939, to September 30, 1940, was forecast at 6,000,000 acre-feet. The actual discharge, according to preliminary calculations was 6,460,000 acre-feet. The error of estimate was, therefore, 7.1 per cent.

The Clearwater at Spalding, Idaho, discharged 8,167,300 acre-feet during the year ending September 30, 1940. The forecast was 6,500,000 acre-feet.

The Columbia at Birchbank, British Columbia, discharged 47,600,000 acre-feet during the period October 1, 1939, to September 30, 1940. The forecast was based on the accumulated annual flow at Trail, British Columbia, and amounted to 39,000,000 acre-feet.

The following tentative conclusions were reached as a result of this forecasting experience:

(1) Dry watershed-conditions during the preceding fall usually, though not always, reduces the runoff from snow-cover.

(2) More than four years' snow-survey record may be required to determine the relationship between water-content of snow-cover and runoff accurately.

(3) Adjacent drainage-areas may not respond alike in runoff even though they are subject to the same storm effects; diversity in elevation, depth of area, and regulating influences make it unsafe to assume such parallel performance.

Division of Irrigation,
U. S. Soil Conservation Service,
Boise, Idaho

REPORT ON SNOW-SURVEYS AND ACTUAL CONDITIONS IN THE COLUMBIA, KOOTENAY, AND OKANAGAN BASINS, AND THE COASTAL BELT ADJACENT TO VANCOUVER FOR 1940

S. H. Frame

In general the forecast from the water-content of the snow-cover in the southern and coastal areas of British Columbia was not very closely reflected in the summer runoff.

Table 1 is a summary of the forecasts, showing the percentage of difference from the normal and actual.

It will be noted from Table 1 that the forecasts, with the exception of that of the Okanagan Basin, were all below normal, ranging from 22 to 50 per cent.

In Mr. Farrow's letter of April 6, 1940, he stated (referring to the unusual winter conditions, lack of precipitation in the form of snow, high temperatures, etc.): "These abnormal conditions render the prediction of runoff from the snow-cover much more difficult than usual.

Table 1

Main basin	Tributary basin	Stream		No. of courses involved	Runoff in per cent of normal		Error	
		Name	At		Forecast	Actual	Per cent of actual	Per cent of normal
Coastal								
Fraser R.	Stave	Stave	Stave Falls	3	32.0	72.7	-55.6	-40.7
Powell R.	.....	Powell	Powell Lake	2	30.1	81.3	-62.7	-51.2
Interior								
Columbia R.	Kootenay	Lardeau	Gerrard	1	69.0	82.6	-30.5	-13.6
Columbia R.	Kootenay	Duncan	Howser	1	64.2	95.9	-32.8	-31.7
Columbia R.	Kootenay	Elk	Elko	2	47.4	70.0	-28.2	-22.6
Columbia R.	Kootenay	Slocan	Crescent	1	49.0	83.4	-39.8	-34.4
Columbia R.	Kootenay	Kootenay	Wardner	3	41.8	79.8	-46.9	-38.0
Columbia R.	Kootenay	Kootenay	Glade	5	50.4	79.6	-36.2	-29.2
Columbia R.	.....	Columbia	Golden	3	49.7	87.8	-43.1	-38.1
Columbia R.	.....	Columbia	Revelstoke	6	45.0	94.5	-52.3	-49.5
Columbia R.	.....	Columbia	Trail	14	55.0	88.0	-39.6	-33.0
Okanagan	Okanagan	Okanagan	Penticton	5	66.5	65.5	+ 3.5	+ 1.0

With only from two to six years' records to work from, and having in mind the peculiar climatic conditions of the past winter, the estimates must of course only be regarded as general indications of what may be expected."

Coastal area--In the Coastal Area the water-content in the snow-cover expressed in the per cent of normal of the runoff of April to July was 31 per cent, the actual runoff was 77 per cent of the same normal and 46 per cent more than was expected. Looking back one can give a reason for some of the discrepancies in forecast. A great deal of the winter precipitation was in the form of rain. Owing to the above-normal temperature, and periods of freezing and thawing, considerable snow melted and ran off before it could be measured. In some cases there was no snow for the end-of-March sampling. During periods when the ground was bare, the precipitation of heavy rains during such times would not appear in the snow-cover measurements at all and, with winter weather as depicted, it can readily be seen what an "unusual" winter it was and how difficult to make a proper forecast.

Okanagan Basin--The forecast for Okanagan Basin was for 66.5 per cent of the normal runoff of April to July. The actual runoff was 65.5 per cent of the same normal and one per cent less than the prediction. The closeness of this forecast is due, I think, in part to the application of the soil-moisture deficiency index of 0.88, otherwise a much lower runoff would have been indicated.

Kootenay-Columbia Basin--In the Kootenay-Columbia Basin the water-content varies widely, somewhat below average and very light at the lower elevations. Melting conditions were the same as those which occurred in the Coastal Area, but not to so great an extent.

East Kootenays--The forecast for the Elk and Kootenay (at Wardner) rivers in this area was for 45 per cent of the normal runoff of April to August. The actual runoff was 75 per cent of the same normal and 30 per cent more than the prediction. The rainfall of April to August, as recorded at the two nearest precipitation-stations, was 73 per cent of the normal rainfall for that period.

North Kootenay Area--The forecast for the Lardeau and Duncan rivers was for 67 per cent of the normal runoff of April to August. The actual runoff was 89 per cent of the same normal and 22 per cent more than the forecast indicated.

West Kootenay and Arrow Lake Area--The forecast for the Slocan and Kootenay (at Glade) rivers was for 50 per cent of the normal runoff of April to August. The actual runoff was 81.5 per cent of the same normal and 31.5 per cent more than the prediction. The rainfall of April to August, as recorded at the two nearest precipitation-stations on a westerly slope, was 103 per cent of normal, while a nearby station on an easterly slope showed 67 per cent of normal.

Columbia Basin--The water-content of the snow-cover in the Columbia Basin shows the same low percentages as in the other basins. The forecast was for 50 per cent of the normal runoff of April to August. The actual runoff was 90 per cent of the same normal and 40 per cent more than that predicted. The precipitation of April to August in the Basin was within one per cent of normal.

Summary--It will be noted in all cases, except in the Okanagan Basin, that the actual runoff was below normal, but owing to the peculiar winter conditions affecting the snow-cover, the forecasts gave indication that it would be much lower than that which actually occurred. However, since the summer precipitation for the most part was near the normal, this would have a tendency to keep the runoff greater than the forecast indicated.

Water Rights Branch, Department of Lands,
Victoria, British Columbia

OREGON STREAM-FLOW FORECASTS AND FACTORS INFLUENCING ACCURACY IN 1940

R. A. Work and J. H. Ryan

Complete data on Oregon stream-performance during the record-year 1939-40 are not available, as the records are only now under review. Sufficient data are available, however, to furnish a general idea of accuracy of the 1940 Oregon water-supply forecasts.

The same forecasting methods were followed as in previous years by water-forecast committees, who made full use of correlations developed by engineers of cooperating agencies.

In reporting 1940 results, we are using the same descriptive terms proposed by the authors at the Seattle snow-survey conference, June, 1940, as shown below:

Percentage by which obtained flow differs from forecasted flow	Adjectives used in describing forecasts
5	Excellent
5 to 10	Good
10 to 20	Fair
More than 20	Poor

Accuracy of the 1940 Oregon water-supply forecasts is shown in Table 1. Accuracy of the 1940 forecasts relative to those in the preceding four years also is shown in Table 1.

The improving accuracy of forecasts is encouraging if indicative of results to be expected of water-supply forecasts based on snow-surveys where correlations are limited or lacking and where there are no climatic irregularities of magnitude during the runoff-season. We believe they are so indicative.

Table 1--Accuracy of all Oregon water-supply forecasts, 1936-1940

Forecast accuracy	1936	1937	1938	1939	1940[a]	Total period
Excellent, number	7	10	21	15	19	72
Per cent of annual total	22.6	23.3	48.8	24.2	34.5	30.8
Good, number	10	13	8	15	17	63
Per cent of annual total	32.2	30.2	18.6	24.2	30.9	26.9
Fair, number	7	8	7	12	11	45
Per cent of annual total	23.6	18.6	16.3	19.4	20.0	19.2
Poor, number	7	12	7	20	8	54
Per cent of annual total	22.6	27.9	16.3	32.2	14.6	23.1
Total, number	31	43	43	62	55	234
Per cent, "Good" or better	54.8	53.5	67.4	48.4	65.4	57.7
Per cent, "Fair" or better	77.4	72.1	83.7	67.8	85.4	76.9

[a]Tentative only, as computations of 1940 stream-flows are incomplete.

U. S. Soil Conservation Service (R.A.W.),
Medford, Oregon
Office of the Oregon State Engineer (J.H.R.),
Salem, Oregon

Improvement of Equipment

CLEANING AND SHELLACKING SAMPLER TUBES BY IMMERSION

Philip S. Cowgill

In connection with the use of shellac for coating sampling tubes, the question of removal is sure to arise. In the case of steel tubes this has been solved by the use of Oakite or by scraping with a boiler-flue cleaner. However, these methods cannot be used with the duralumin tubes because of the certainty of injuring the metal.

However, ordinary commercial denatured alcohol is not injurious to duralumin and is a very efficient solvent of shellac. Figure 1 shows a tank used for immersing the tubes in alcohol. It was built in the shop of the Sierra Pacific Power Company of scrap.

A tube which has been given two or three coats will come out of the alcohol perfectly clean in about 20 minutes, while it may require from 45 minutes to an hour to remove an accumulation of eight or ten coats, but if time enough is allowed, the tube will come out as clean as when new.

This same tank is also used for shellacking the tubes by immersing them. For this purpose it has been found that the commercial liquid shellac is much too thick. When a tube is hung up to drain after dipping, the shellac tends to accumulate in globules and will begin to stiffen before it can drain cleanly, thus leaving the coating lumpy and irregular in appearance. If the shellac is diluted in the proportions of about three parts commercial shellac to one part

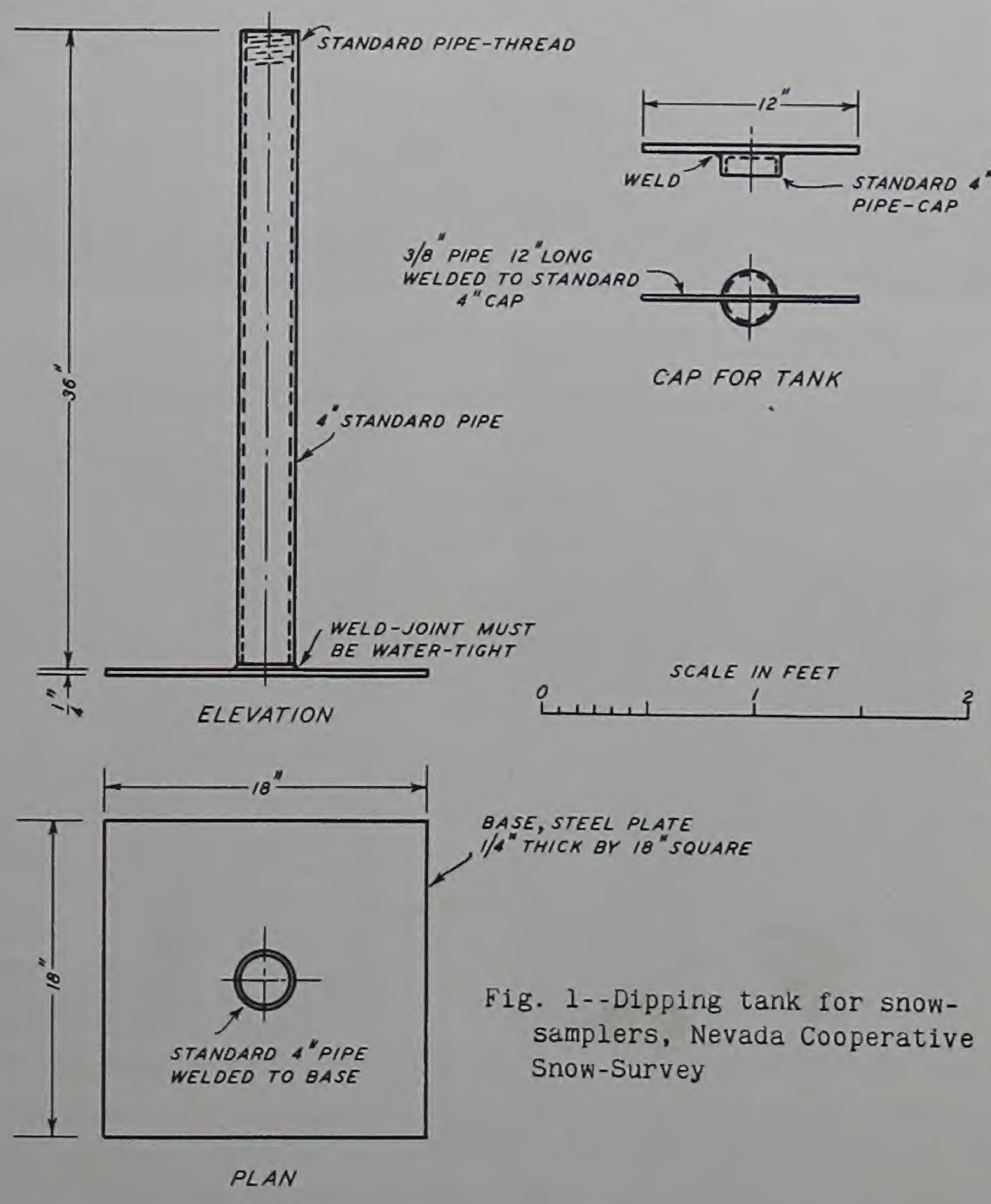

Fig. 1--Dipping tank for snow-samplers, Nevada Cooperative Snow-Survey

denatured alcohol, it will flow freely and drain off quickly leaving a velvety appearing coat on the tube.

In using the old swab-and-brush method, one coat seemed to be inadequate as freezing often resulted. My experience indicated that at least two and preferably three coats were required to insure protection. I have thought that this was because of the lack of uniformity of the swab-method which was likely to leave numerous uncoated spots. Inasmuch as the immersion-method leaves an absolutely uniform coat it seems quite possible that with this method one coat may be sufficient. I plan later in the season to make some tests using tubes having one, two, and three coats and an uncoated tube, simultaneously.

It has been found that three complete 20-foot sets can be coated by the immersion-method in less time than was required to coat one set with a swab, and there is far less muss. A small wire hook with a shank four or five inches long is inserted in the spanner-wrench hole, the tube is immersed, withdrawn, and hung up over the tank to drain, after which it is hung by the same hook on a convenient nail somewhere out of the way and left to dry thoroughly. The draining process requires possibly two or three minutes. Each coat must be allowed to harden thoroughly before the next one is applied. It is desirable to allow at least 24 hours for this process and a 48-hour period seems to give better results.

Sierra Pacific Power Company,
Reno, Nevada

A REVIEW OF CHATILLON AND SONS' LATEST SPRING BALANCE FOR THE MOUNT ROSE SNOW-SAMPLER

Philip S. Cowgill

The latest design of a spring-balance submitted by Chatillon and Sons to the Snow-Survey Conference at Seattle [Trans. Amer. Geophys. Union, 1940, p. 908, Fig. 1, No. 2] won immediate approval from the snow-surveyors for its compactness, readability, and weight in addition to the accuracy expected from its iso-elastic springs.

The dial-range of 1 to 100 in place of the former range of 1 to 160 makes mental computation easier if the pointer makes more than a complete turn of the dial. The numbers also are conspicuous and the graduations plainly visible. Furthermore, the round draw-bar permits some lateral twisting without friction and closes the orifice against snow.

Some changes, however, are essential to correct obvious defects:

(1) The suspension-bar should be lengthened to prevent retraction within the case and catching on the inner edge of the orifice when withdrawn.

(2) The adjustment to 0 should be expanded to a whole turn of the dial or one-half turn from the center of the adjustment screw. This may require a lengthening of the case by 3/4 inch. The adjustment also should be more firmly built into the case and made to turn more readily. A brake should be attached to prevent turning of the screw during carrying from station to station of the course.

(3) The framework of the case is possibly too light to withstand rough usage when carried in the pack. A cover should be provided for the dial.

(4) To protect the eyes against unnecessary reflection, the case, like the dial, should be dull-finished. New snow, burnished metal, and calm water in full sunlight are ruinous to sight.

(5) The usual lack of special screw-drivers in the field, where emergency repairs may be necessary, makes it desirable to equip the balance with the simple screw that can be turned by a knife.

Sierra Pacific Power Company,
Reno, Nevada

A NEW DESIGN FOR A CANVAS CASE TO CARRY SNOW-SURVEY TUBES AND ACCESSORIES

Philip S. Cowgill and Carl Elges

The problem of carrying sampling tubes for considerable distances on skis has always been more or less troublesome. The making of the aluminum tubes in short sections has helped materially, but a convenient carrying case has not yet been supplied.

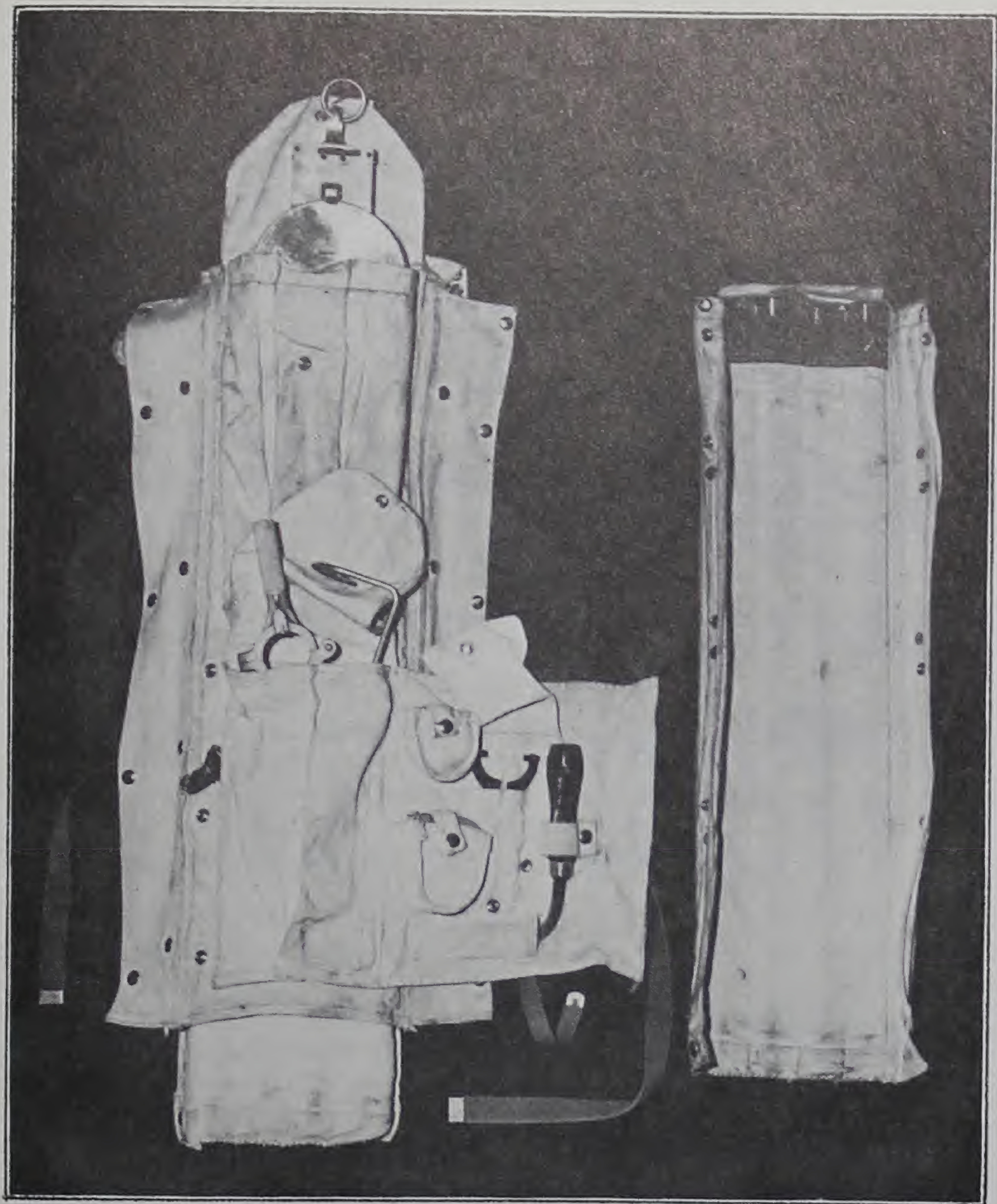

Fig. 1-A Fig. 1-B

Fig. 2

Fig. 3

Fig. 1--Canvas carrying case for snow-sampler outfit [(A) Rear view of carrying case opened to show the various pockets and contents; (B) case for extra sections of sampler, which can be enclosed between the two faces of (A) or carried separately with or without knapsack as a second pack]

Figs. 2 and 3--Complete case fastened in place for transport on the trail

The case shown in Figures 1 to 3 was developed with the idea of making a pack which could be carried on the back by itself or fastened across a knapsack. The entire outfit including balance, tape, cleaning hook, etc., is contained in one case. Since there is often no need of more than ten feet of tube, the case is made in two units, each holding four sections. The second section can be removed and left behind if desired or can be tied across a knapsack while all the accessories are still with the first four sections. Wide-web shoulder straps make for ease of carrying while the belt holds the pack in position on the back and prevents its shifting from side to side.

The method of fastening the case together has been the subject of some discussion, the efficiency of the snaps being questioned. It has been suggested that laces be used, but lacing would be slow and moreover would be difficult if not impossible with numbed hands. Zippers have also been suggested but they often freeze and clog. Overshoe buckles have been suggested and would probably prove very satisfactory, being easily operated even with numb hands and readily freed if frozen. They have the added advantage of being adjustable, thus giving opportunity to take up slack or to compensate for shrinkage of material. The principal drawback is that in heavy brush they might catch and become unfastened, but this is unlikely to happen to any great extent.

The present tendency of the seams to rip open under strain can be overcome by the use of leather reinforcements.

Sierra Pacific Power Company (P.S.C.),
Nevada Agricultural Experiment Station (C.E.),
Reno, Nevada

AN IMPROVED ESCAPEMENT FOR RECORDER CLOCKS

Frederick Better
(Presented by James E. Jones)

The clock is the heart of any continuous recorder, and, as "clock-trouble" is the cause of about 90 per cent of lost records, I have endeavored to remedy this condition by improving the escapement. This small integral part is likewise the heart of the clock and, therefore, is the subject of my paper (Fig. 1).

On account of the remote locations of most continuous water-stage recorders and recording precipitation-gages it was my idea that if the escapement only could be easily detached and replaced by a standard part, leaving the rest of the mechanism intact, clock-stoppage could be reduced to a minimum.

The foundation of base-plate of this escapement unit is a solid brass plate mounting the balance-wheel with the Elinvar hair-spring and its regulating lever, the double roller and shaft, and the escapement and shaft. This rigid unit can be removed and replaced in 30 seconds in the field by the average attendant by means of a single thumb-screw. Due to the shape of the base-plate it is keyed into proper position without further adjustment, or danger of binding.

The escapement has five jewels and is constructed like a watch, to run in hot or cold temperatures, with a variation between five and ten minutes a month. The countersunk oil-cups are sufficient for running two to two and one-half years without additional lubrication. These few interchangeable parts can be repaired or overhauled by any competent watchmaker at small cost.

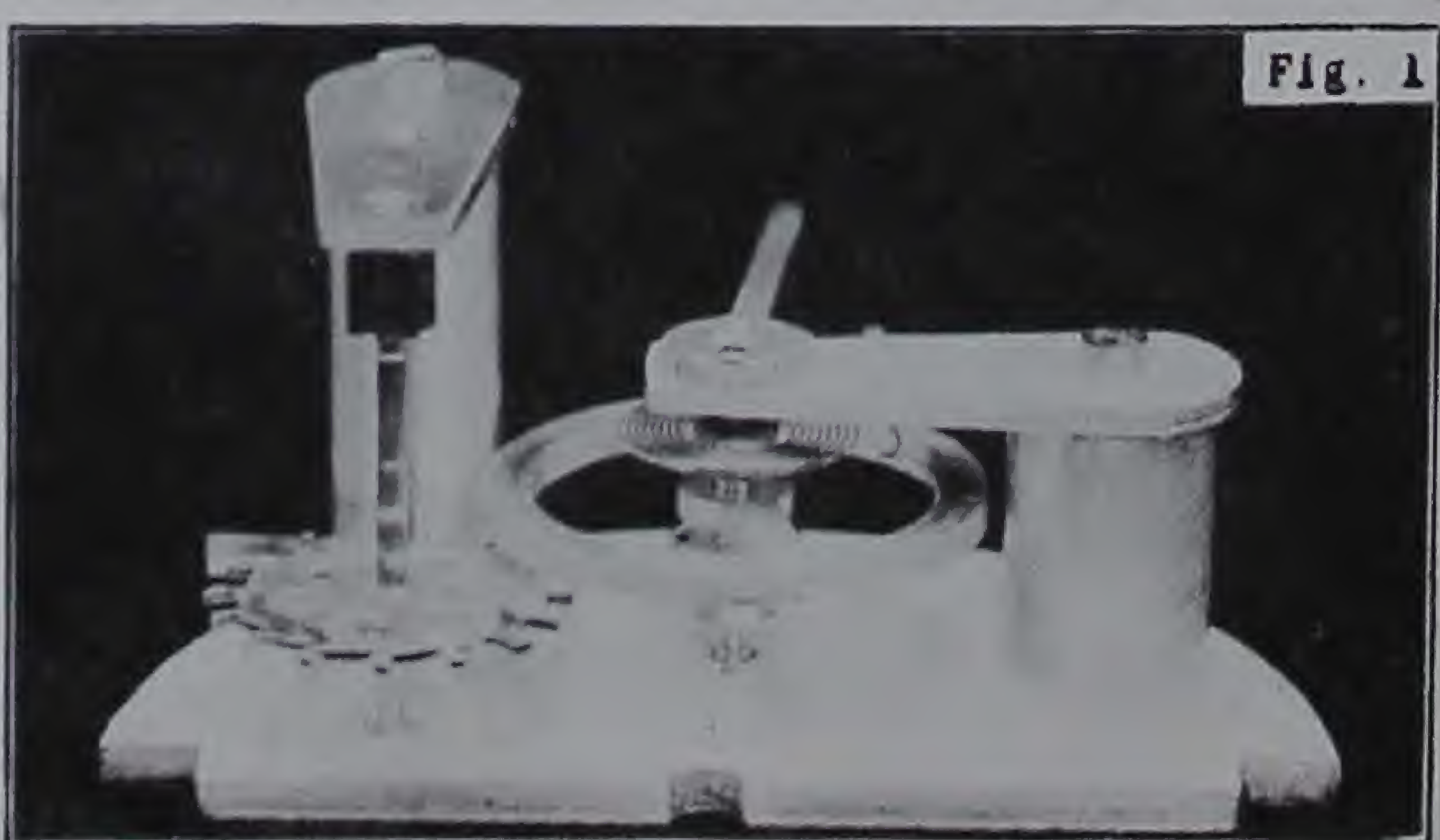

Fig. 1

This small compact unit also eliminates the expense of spare clocks, and is much more convenient to carry around or mail in for repairs. One escapement, installed in a clock in the High Sierra, has run for three years without repairs.

Escapements of this type that are now in service are all made by hand and, unfortunately, it will be necessary to continue their manufacture in this manner since under existing world conditions it is not possible to obtain dies ordered from Switzerland. However, the cost of the hand-made product is considerably less than the cost of a new clock, and its use can easily be justified by the reduction in percentage of lost records not to mention the time and expense involved in removing and repairing the entire clock-mechanism.

Los Angeles, California

TEST OF SNOW-SAMPLING TUBES OF LARGE AND SMALL DIAMETER

Bertram C. Goodell and Kenneth L. Roberts

The preliminary test of snow-sampling equipment discussed in this paper was made in March, 1939, on the Merrimack Flood-Control Survey under the supervision of the Northeastern Forest Experiment Station.

Types of equipment tested--The smaller tube consisted of two sections of tubing of the Mount Rose type, with a total length of five feet and an inside diameter a little larger than the cutter. The inside diameter of the cutter was 1.485 inches, making one ounce equivalent to one inch of water. The scales for this tube were of a tubular type, graduated in ounces, but readings could be estimated to one-tenth of an ounce which was equivalent to one-tenth of an inch of water.

The larger tube was home-made from a five-foot piece of aluminum tubing with a slightly larger inside diameter than the cutter. The inside diameter of the cutter was 2.787 inches, making one gram equivalent to one-hundredth of an inch of water. With this tube heavy scales were used with a large circular dial-reading to the nearest gram or one-hundredth of an inch of water.

Observations of snow-water equivalent made with both types of equipment--In order to determine the accuracy of the small Mount Rose type snow-tube and the large home-made tube the following test was conducted. A location was chosen in a hardwood understocked type where snow-depths appeared uniform and the soil was unfrozen. Samples were taken in a gridiron-pattern over an area of approximately ten by 20 feet, alternate rows of samples being taken by one observer with the small tube and by a second observer with the large tube. Individual samples were taken about six inches apart each way. Weights were estimated to tenths of ounces on the tubular scales and read to grams on the gram-scales. Results of 32 measurements with each set of equipment were:

	Small tube	Large tube
Number of samples	32	32
Mean water-equivalent, inches	7.42	7.47
Standard deviation, inch	0.58	0.69
Standard error of mean, inch	0.10	0.12
Coefficient of variation, per cent	7.82	9.24

The smaller coefficient of variation in the measurements taken with the small Mount Rose type tube and scales indicates that this equipment appears to be somewhat more reliable when the average obtained with each of the tubes was compared with the average of all 64 observations. In order to eliminate the differences in accuracy of the two scales used, another series of samples was taken in which only the gram-scales were used for weighing both tubes. The ratio between the squares of the diameters of the two tubes was then applied to convert the snow-weight taken with the small tube to values comparable with the samples taken with the large tube.

Results of additional 15 measurements using the gram-scale for weighing both tubes were:

	Small tube	Large tube
Number of samples	15	15
Mean water-equivalent, inches	9.16	9.09
Standard deviation, inch	0.45	0.53
Standard error of mean, inch	0.12	0.14
Coefficient of variation, per cent	4.91	5.83

The coefficients of variation from this test bear the same relation to each other as those in the first test indicating the small tube to be somewhat more reliable.

In both sets of observations the means obtained with the two tubes agree so closely that the differences are probably entirely due to small accidental errors rather than to any consistent differences attributable to the tubes or observers.

The tests made seem to indicate that the small Mount Rose type snow-sampler when used either with the standard tubular scales or with the more accurate gram-scales gave slightly more reliable and consistent results than the larger tube used with the gram-scales. In any event the tests do not bear out the hypothesis that a larger sampling tube gives greater precision in snow-sampling measurements.

Relative efficiency and convenience of the two types of equipment--Because of many difficulties encountered on snow-surveys the ease with which equipment can be carried and used is of great importance. After using the equipment in the field for several weeks some observations were made concerning the relative practicability of the two types.

The only advantage of the large tube was that the soil-plugs could be removed more readily from the lower end whereas the small tube has many practical advantages. The small tube was incomparably more portable. The snow-cores were held in the small tube more consistently than in the large one because of the smaller diameter and the greater difference between the diameter of the cutter and that of the tube. For moderate snow-depths the small tube could be handled easily by one man but with the large tube and scales it proved necessary to either hang the scales on a support or have a second man along to hold the scales. There was little difference in the difficulty encountered in forcing the two types of tubes down through crust and ice-layers but the cutting teeth of the small tube were of superior design and material and were more resistant to dulling or bending. The larger shoulder between the cutter and the smaller tube seemed to protect the paraffin coating of the tube so that less frequent renewals were necessary.

Conclusion--Under the conditions encountered in this test the small Mount Rose type of equipment proved to be more practical and just as accurate as the large tube and scales. Further tests might be made using a larger number of observations and a procedure to eliminate the personal equations of the observers to check the comparative accuracy of the two sizes of tubes, but there is no indication that the larger tube would show any significant advantage to outweigh its disadvantages. It also might prove worth while to check the desirability of tubular scales with a capacity of about 30 inches (inclusive of the tube-weight) and reading to quarter-ounces in order to try to improve the accuracy of moisture-content determinations in snow of moderate depth.

Northeastern Forest Experiment Station (in cooperation with Yale University),
New Haven, Connecticut

THE DURALUMIN SNOW-SAMPLER UNDER STRAIN: A DISCUSSION

Because of its light weight, the duralumin snow-sampler has maintained its popularity in competition with steel samplers despite inherent defects which have long been discussed and to a considerable extent can be corrected.

The following correspondence indicates present weaknesses under severe conditions and some corrective steps.

PHIL E. CHURCH (University of Washington, Seattle, Washington)--During spring vacation toward the end of March, my student from Mount Rainier was able to make only one sampling. There were altogether too many people on the mountain, and his sampling was done when he had spare time from his regular duties. He has had some trouble with the instrument. For example, in a 127-inch column, he found four inches of solid ice at the bottom. In trying to get the

instrument through that crust, several teeth from the bit were broken.

The driving-wrench key slips out of the slot when the sampler is embedded in the heavy snow with crusts on Mount Rainier. In attempting to drive the sampler through the ice-crust at the bottom, on his second attempt, my student reports that the sleeves on the ends of the sections of the sampler began to turn. Fortunately, he was able to get the whole instrument back up through the snow.

Still a third difficulty that he encountered was that the spanner-wrenches would not take a sufficient hold in the holes to permit him to unscrew the sections after the sampling was completed. In fact, he had to ski a mile and half down hill with a 180-inch sampler completely assembled. He has also reported that above Edith Creek Basin the surface is icy, convex, and windy so that the snow does not remain.

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--Do not be discouraged about the failure of the snow-sampler. If the sampler can penetrate one inch of ice, it has done well. Your assistant has penetrated four inches. When teeth are broken off we file other teeth in their place at least temporarily. Meantime better write to Mr. Marr and ask him for one or two spare cutters or better still to send you another first section containing the cutter while you send your section back to him for repairs.

The wrench may not have been placed tightly around the sampler or possibly it is one of the old make that has the corners rounded off so that it acts like a sled and slips down beyond the slot while denting the wall in.

It has long been recognized that the couplings should be soldered and riveted both. Apparently those of your sampler were merely shrunk on. We can also look into the matter of the driving wrench and see whether it will not be possible to enlarge and change the contour of the tongue that enters the slot and supposedly prevents the wrench from sliding down from overload.

The spanner-wrenches also are of a cheap Mason-jar variety, and certainly cannot be depended upon to maintain their positions in the holes when the couplings are very tight. A much better wrench has been designed [Trans. Amer. Geophys. Union, 1938, p. 715, Fig. 1] but because of the cost of the dies it has never been made in quantity. It should not be expensive to have a blacksmith make a wrench of far greater dependability than the one you now have.

PHIL E. CHURCH--This past week-end I attended the meetings of the Columbia Basin Interstate Water Forecast Committee and had had correspondence from Mr. Marr previous to my trip. Because Mr. Marr was present at Portland, I took the snow-sampler to him. He is going to have it repaired and sent back to me next winter. I told him of the troubles we have had with it and he assured me that we have not experienced anything new.

Reports on Investigations

CORRELATION OF STREAM-FLOW AND SNOW-COVER IN COLORADO

R. L. Parshall

The project, Snow-Surveys and Irrigation-Water Forecasts, now carried on in the western mountain States is conducted in many of the States under the direction of the Division of Irrigation, Soil Conservation Service, and for Colorado, Wyoming, New Mexico, and Arizona this work is supervised through the office at Fort Collins, Colorado. The project is a cooperative one in which various Federal, State, and other agencies help in making possible this work. Because of the nature of this particular project there is a wide-spread interest in the information made available to the public through the results of the snow-surveys.

The problem of forecasting stream-flow as a seasonal water-supply for irrigation, dependent upon the preceding winter's snow-cover, is one of real importance to those who live in the arid west.

Forecasting the runoff as related to snow-cover is, in many cases, not a simple problem. Generally, the present plan is to sample the snow-cover systematically over a limited definite area, called a snow-course, and then correlate the extent of water held in the snow with the amount of runoff the following season.

This relation is often complicated and requires the introduction of legitimate factors whereby correction-coefficients may be applied to enable closer approximations of the predicted stream-flow. It is likely that with more experience with this problem it will be found that better agreement between the actual and forecasted runoff can be expected when these factors are considered. Good correlations with no corrections applied are obtained for certain streams, but in others wide variations are found.

Let us consider a few of the influencing factors that are believed to be contributory to the apparent inconsistencies of the relation of snow-cover and runoff. The runoff resulting directly from snow-cover cannot be determined readily in all cases. In regions where there is a so-called wet and dry season, it is quite reasonable to assume that the runoff is from snow-cover alone because of the absence of late spring and early summer rainfall. At Fort Collins, a 50-year continuous precipitation-record shows that, as an average, 43 per cent of the total annual rainfall occurs during May, June, and July. For 1901, it was 50 per cent; 1908, 62 per cent; and 1904, 69 per cent. For the deficient year, 1919, the May-June-July rainfall was only 12 per cent of the total for the year. For 1940 the summer showers were of such proportion that little or no surface-runoff reached the main stream as added flow. In 1901, the May precipitation was 7-1/2 inches; in 1908 nearly 6 inches; and in 1904 about 5-1/2 inches. These rather excessive May precipitations did materially affect the stream-flow and could in no way be credited to the runoff from the melting snows in the mountain area.

Because of the mixed source, it appears that for some streams forecasting within close limits will not be possible.

Other factors bear upon the final figure as to the most probable amount of the anticipated supply. The location and characteristics of the snow-course may have a bearing upon the final conclusion of the forecast; the matter of soil-moisture conditions in late fall, or time of freezing, is a factor believed to be important as an index to runoff; and it is not unlikely that a relation might exist between the rate of accumulation of snow-cover and runoff, that is, light or heavy early winter snows.

Topography and nature of terrain are factors to be considered, as well as extent and type of vegetal cover over the drainage. Also, exposure, altitude, color, and nature of the ground-surface may be regarded as factors related to runoff. These, together with meteorological elements such as temperature, wind, and humidity as affecting evaporation-loss from the snow, all influence the forecasting problem.

It is reasonable to assume that these various components are possible of evaluation within certain limits, and ultimately it is believed, through study and research together with experience of the characteristics of individual drainage-basins, corrections may be determined that will in the future permit close approximation of the season's predicted supply.

Because of the geographical location of Colorado, straddling the Continental Divide, with major streams heading in the high mountain areas and flowing north, east, south, and west through irrigated valleys, conditions should be favorable for snow-surveying and permit reliable forecasts of water-supplies. Colorado is a mountainous state credited with 49 peaks that are more than 14,000 feet in elevation and more than 1,000 having an elevation greater than 10,000 feet. In these Colorado mountains, more than 75 snow-courses are now located--some of which were established in the summer of 1935 and a limited number located during the fall of 1940. On some of the drainages five years of record are now available for the purpose of establishing a temporary relationship between the water-content of the snow-cover and the subsequent runoff.

Forecast diagrams

A limited selection of graphical relations, as pertaining to Colorado streams, has been made and presented to show typical plotting of points and approximate forecast-curve based on four- and five-year records of the April 1 water-content of the snow as correlated with the aggregate April to July stream-flow the following season.

Table 1--Arkansas River, based on runoff at Salida, Colorado, for snow-course 19 at Tennessee Pass, elevation 10,200 feet (see Fig. 1)

Year	April 1 water-content snow-cover, inches	Runoff, thousands acre-feet	Curve value, thousands acre-feet	Differ-ence, thousands acre-feet	Devi-ation, per cent
1936	13.1	347	347	0	0
1937	6.6	225	196	29	13
1938	10.7	292	286	6	2
1939	9.0	256	250	6	2
1940	5.2	142	160	18	13
		Mean deviation			6

Table 2--Colorado River, based on runoff at Glenwood Springs, Colorado, for snow-course 1 at Cameron Pass, elevation 10,200 feet (see Fig. 2)

Year	April 1 water-content snow-cover, inches	Runoff, thousands acre-feet	Curve value, thousands acre-feet	Differ-ence, thousands acre-feet	Devi-ation, per cent
1936	28.7	1789	1920	131	7
1937	15.3	1063	920	143	13
1938	26.7	1938	1790	148	8
1939	23.0	1302	1500	198	15
1940	17.6	934	1100	166	15
		Mean deviation			12

Table 3--North Platte River, based on runoff at Saratoga, Wyoming, for forecast-curve for average of nine snow-courses, of average elevation 9,200 feet, located on this drainage in Colorado and Wyoming (excess precipitation occurred over this drainage above Saratoga during May and June, 1938; see Fig. 3)

Year	April 1 water-content snow-cover, inches	Runoff, thousands acre-feet	Curve value, thousands acre-feet	Differ-ence, thousands acre-feet	Devi-ation, per cent
1936	22.2	665	710	45	7
1937	18.1	525	480	45	9
1938	20.1	775	590	185	24
1939	17.3	399	440	41	10
1940	14.9	344	310	34	10
		Mean deviation			12

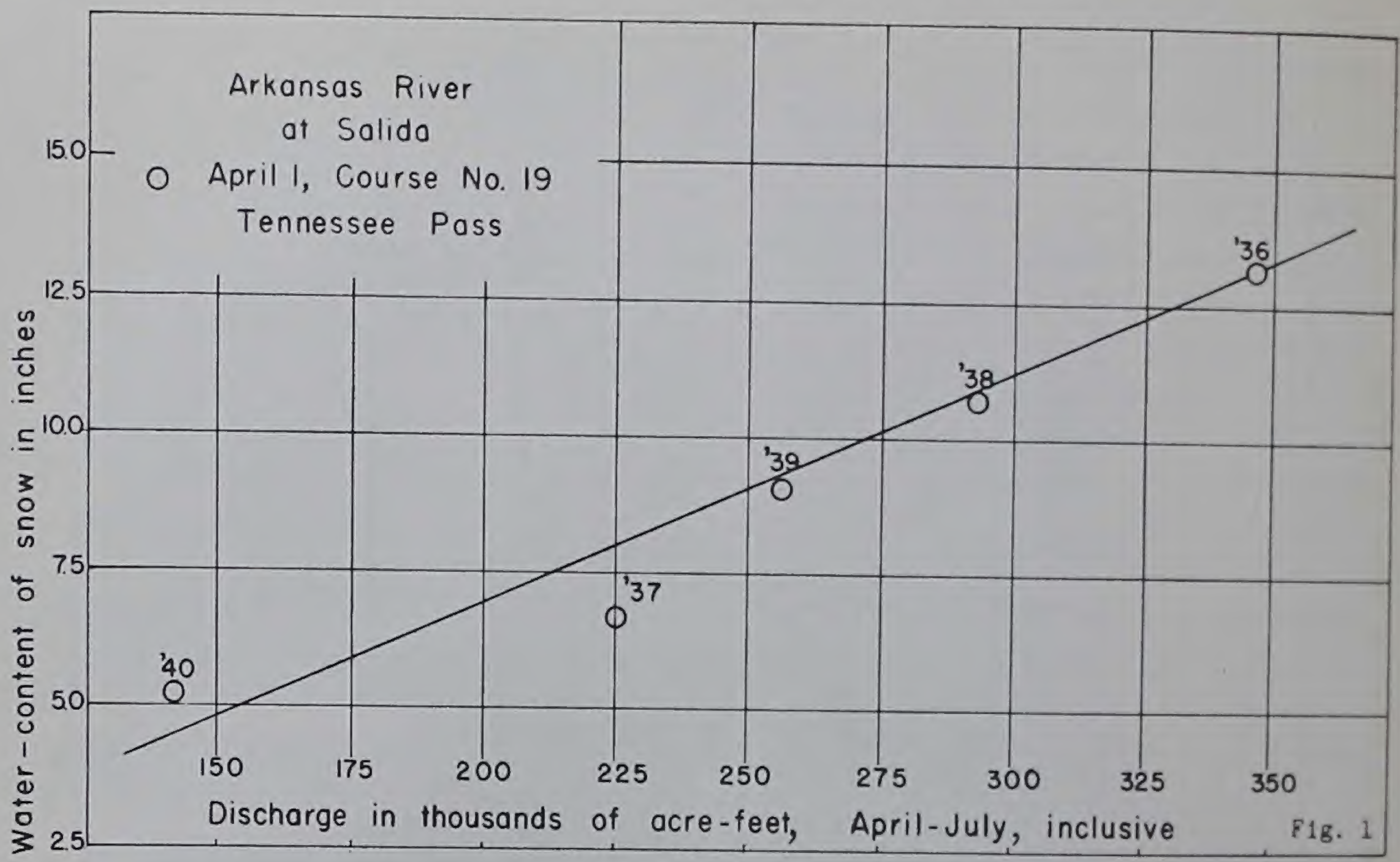

Fig. 1

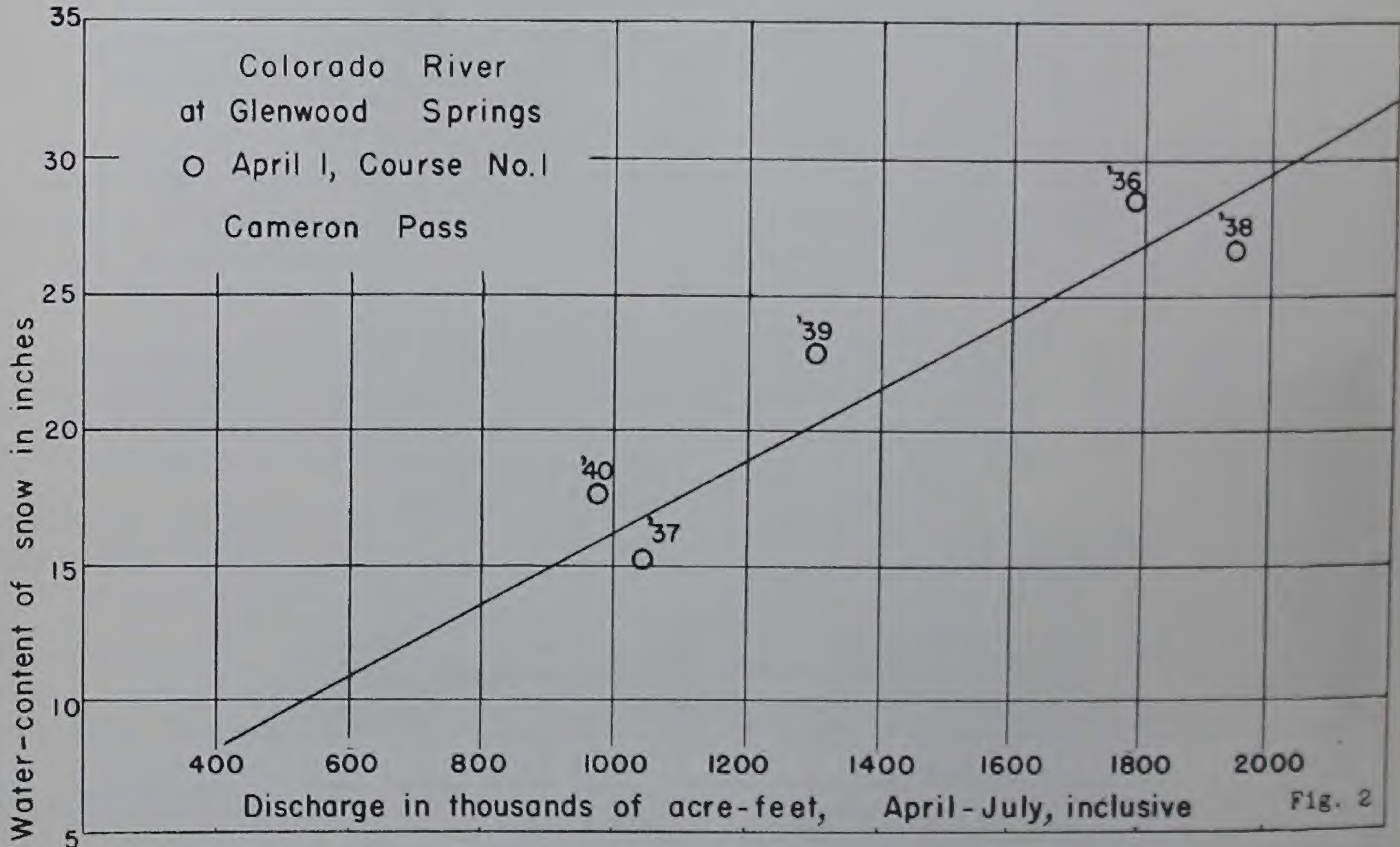

Fig. 2

Photographic method of forecasting

Studies are now under way to investigate the relation of the extent of snow-cover over a definite and large area above timber-line to that of runoff where the index is expressed as a percentage of the cover indicated by photographs taken at certain dates from a fixed viewpoint. The area selected for study is rugged enough so that maximum snow-cover will not completely submerge the ground-surface, and a light snowfall would be sufficient to indicate a definite contrast in the view.

The method consists of taking a photograph of the high mountainous area chosen for such a study, with an eight- by ten-inch telephoto camera, and then enlarging that portion of the picture to be investigated to a sufficient size for close inspection. Over the enlargement is placed a clear piece of photographic film ruled into 100 equal divisions. After the film is ad-

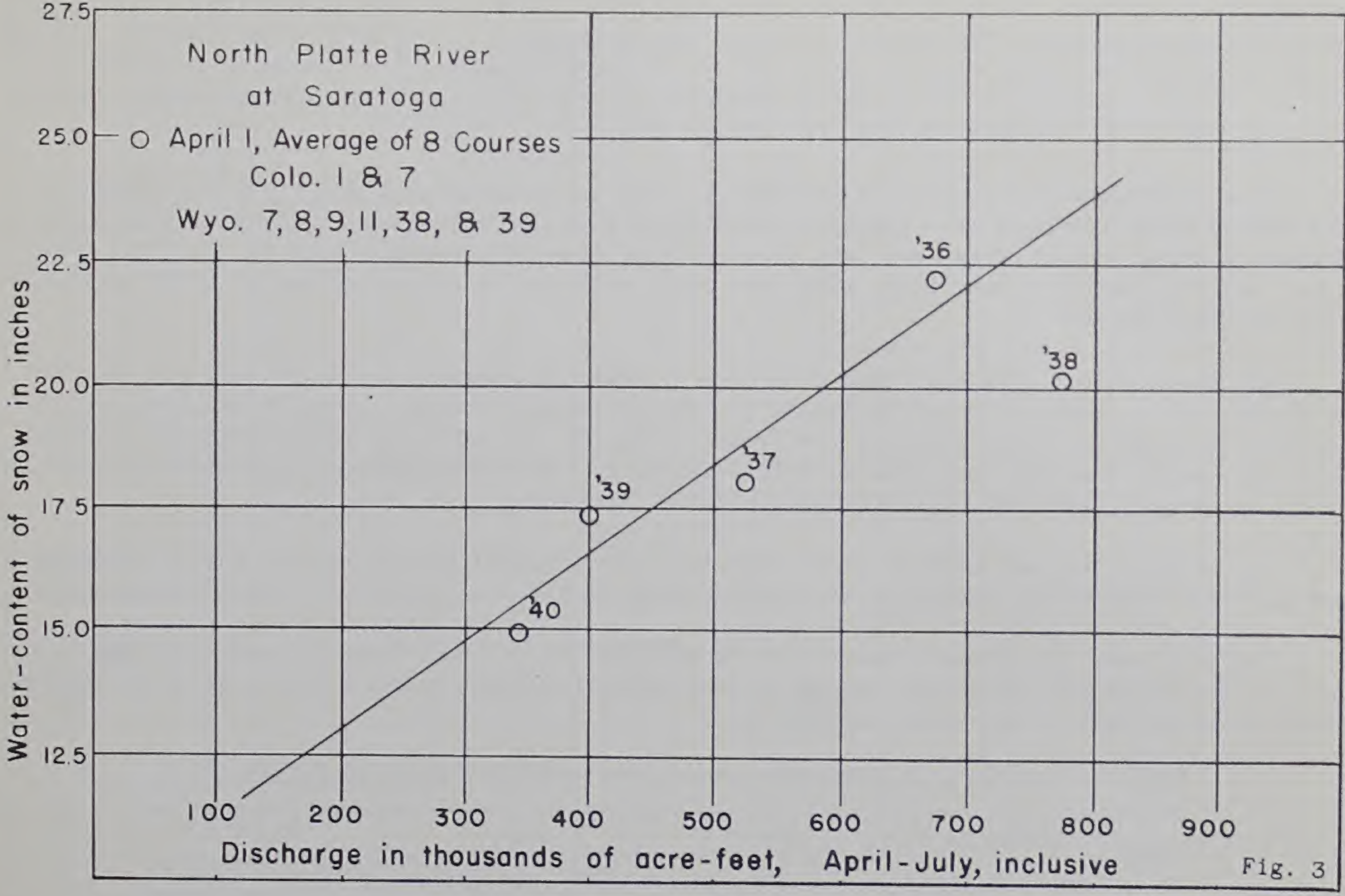

Fig. 3

Fig. 4--Snow-cover, Comanche Peak, February 1, 1938

Fig. 5--Snow-cover, Comanche Peak, May 1, 1938 (enclosed area used for analysis)

justed to its correct position, the percentage of area covered by snow in each individual division is then estimated. The average of these 100 observations, limited to the definite selected area, is considered to be the percentage of area covered by snow. The method of procedure is similar to that reported by H. L. Potts, engineer, of the Denver Municipal Water Board, in the Transactions of the American Geophysical Union, 1937.

This investigation was started February 1, 1938, covering a portion of the high range on the Poudre River Drainage with Comanche Peak selected as the test-area. Very excellent photographs of this mountain area have been taken within a few days of the first of February, March, April, and May for the years 1938, 1939, and 1940, with the exception of May 1, 1939, which was delayed until May 15.

The snow-cover on Comanche Peak, February 1, 1938, is shown in Figure 4, and the contrast in cover, May 1, 1938, is shown in Figure 5. The rectangular space indicates the location of the test-area on the north slope of the peak. It is the intention to secure airplane pictures over the entire Comanche Peak Area at intervals during the winter months. The first picture was taken December 1, 1940, at an elevation of 13,000 feet.

The ratio of the per cent of snow-cover to water-content improves as the winter advances and by May 1 this ratio appears to approach a limit of three per cent per inch of water-content.

Table 4 shows the trend of snow-cover by analysis of the photographic record and the relation to the water-content as determined by snow-surveys on Cameron Pass course which is located about 12 miles west of the Comanche Peak Area.

Table 4--Per cent of snow-cover and water-content of snow at Cameron Pass

Year	February 1		March 1		April 1		May 1	
	Per cent	Inches	Per cent	Inches	Per cent	Inches	Per cent	Inches
1938	53.7	....	76.5	20.2	84.0	26.7	95.0	31.6
1939	56.6	13.8	59.6	17.2	77.2	23.0	75.6[a]	26.4
1940	57.3	9.5	69.8	15.4	68.1	17.6[b]	67.1	22.4
	Per cent of cover per inch of water-content							
1938	....	....	3.8	....	3.2	....	3.0	....
1939	4.1	....	3.5	....	3.4	....	2.9[a]	....
1940	6.0	....	4.5	....	3.9	....	3.0	....

[a]Photograph May 15, water-content May 1.
[b]Water-content doubtful. March 15, observation 20.2 inches.

Figure 6 shows the correlation on April 1 and May 1 of percentages of snow-cover with the inches of water-content for Cameron Pass Snow-Course. The conditions for April indicate close agreement and, assuming this to be the true position of the calibration-curve, it then will be necessary only to find the percentage of snow-cover April 1 and then determine the corresponding water-content in the upper part of the diagram. This value of the water-content when applied to the lower part of the diagram will show the probable runoff of April to July from the Poudre Watershed.

Conclusion

The ultimate success of reliably forecasting runoff for Colorado streams, as based on snow-surveys, cannot be definitely stated at this time because of the limited period of records available for correlation. In some of the forecast diagrams presented here, fair agreement is to be noted while in others rather wide variations appear. In some instances, the record of surveys on snow-courses located in an adjacent drainage indicates as good if not better correlation than for the course on the stream itself.

The selection of streams for discussion covers three of the main rivers in Colorado, namely, the Colorado, Arkansas, and North Platte. The diagrams showing the forecast curves are merely to indicate temporary relation now existing between water-content in the snow and subsequent runoff.

The summer flow of 1938, in almost every case, appears to be much in excess over that indicated by the April 1 surveys. Comparison of May precipitation, 1937, 1938, 1939, over the

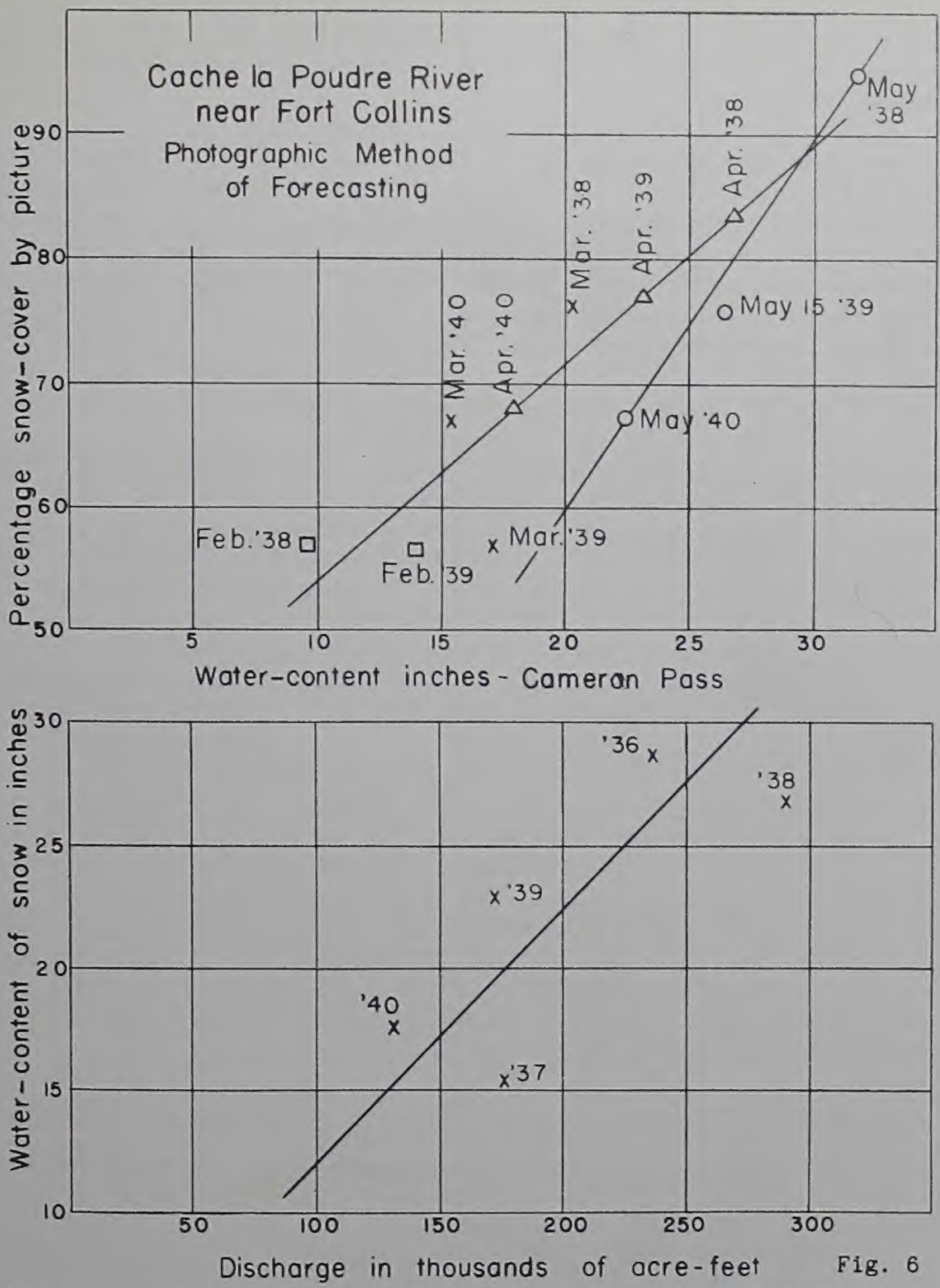

Fig. 6

individual drainage-areas of the streams mentioned shows that of 1938 to be considerably in excess over 1937 and 1939. This fact, no doubt, has some bearing on the apparent deviation of the predicted flow for this particular year.

The photographic method of forecasting appears to have promise as shown by the April 1 relations for 1938, 1939, and 1940. The record is too limited in time to base conclusions as to the final success of this method of forecasting.

Division of Irrigation,
Soil Conservation Service,
Fort Collins, Colorado

TYPE CURVES AND VARIABILITY OF ANNUAL SNOWFALL: STATE OF WASHINGTON

Phil E. Church

Some phases of the snow-cover of the State of Washington have been reported. These include the average depth on the ground on the 15th and last of each month of the snow season [see 1 of "References" at end of paper], the average duration of snow-cover [1,2], and curves representative of types and their areal distribution [2]. Certain features of the cover during the 1939-40 season in the Cascade Mountains [3] and particularly at Snoqualmie Pass have been published [4]. Other characteristics of the snow-cover are being studied and will be reported from time to time.

These studies are similar in many respects to those being pursued by R. G. Stone for New York and New England [5,6] and by Eric Miller for Wisconsin [7] except that a shorter data peri od has been used for Washington.

Because of the lack of adequate assistance for reducing all the snow-data, both published and unpublished, it has been necessary to use a period of not more than 23 years ending with th 1936-37 season. No attempt has been made to adjust shorter-period stations; in analyses of the various features greater reliance has been placed on the data of those stations having a complet unbroken record than on the short-term stations. Thus far the records from 108 stations have been reduced. For each station the average depth on the ground on the 15th and last of each month, the mean annual total, least and greatest amounts, median, and the standard deviation and coefficient of variation (of the mean annual only) have been computed. All original data have come from the United States Weather Bureau records on file in the Seattle Office.

Curves representative of types (annual)--A separate graph of the average depth on the ground on the 15th and last of each month for all stations was made from the data of Table 1. These graphs were then sorted into groups having certain similar characteristics. Of the characteristics used the main ones were shape of curve, continuous or discontinuous cover, dates of maximum depth, secondary maximum and minimum, depth of cover at time of maximum depth, and the time (dates) of maximum depth-increase. The whole procedure has resulted in singling out six main types [2] to which, when subjected to revaluation, was added another. Also some of the main types were further subdivided into subtypes. Gradations from one type to another naturally occur; in some places the transition-zone is quite wide and in others it is very narrow. As a result some curves fit well into two types especially near the boundary drawn between them. The criteria of the main types and their subtypes are given in Table 2.

No attention was given to the location of the stations as the graphs were being sorted into the main types. When plotted areally (see Fig. 1), however, it was found that the types were logically distributed in an orderly manner. The arrangement showed a definite relation to altitude, exposure, windward or leeward mountain slopes, mountain tops and gaps, and water-bodies (Pacific and Inland Waters). As in New York and New England, the distribution of the types indicated that the main control is topographic. In the analysis of a type found in both eastern and western Washington, similarity of form was not assumed to mean similarity of physical causes though it was strongly suggestive of such.

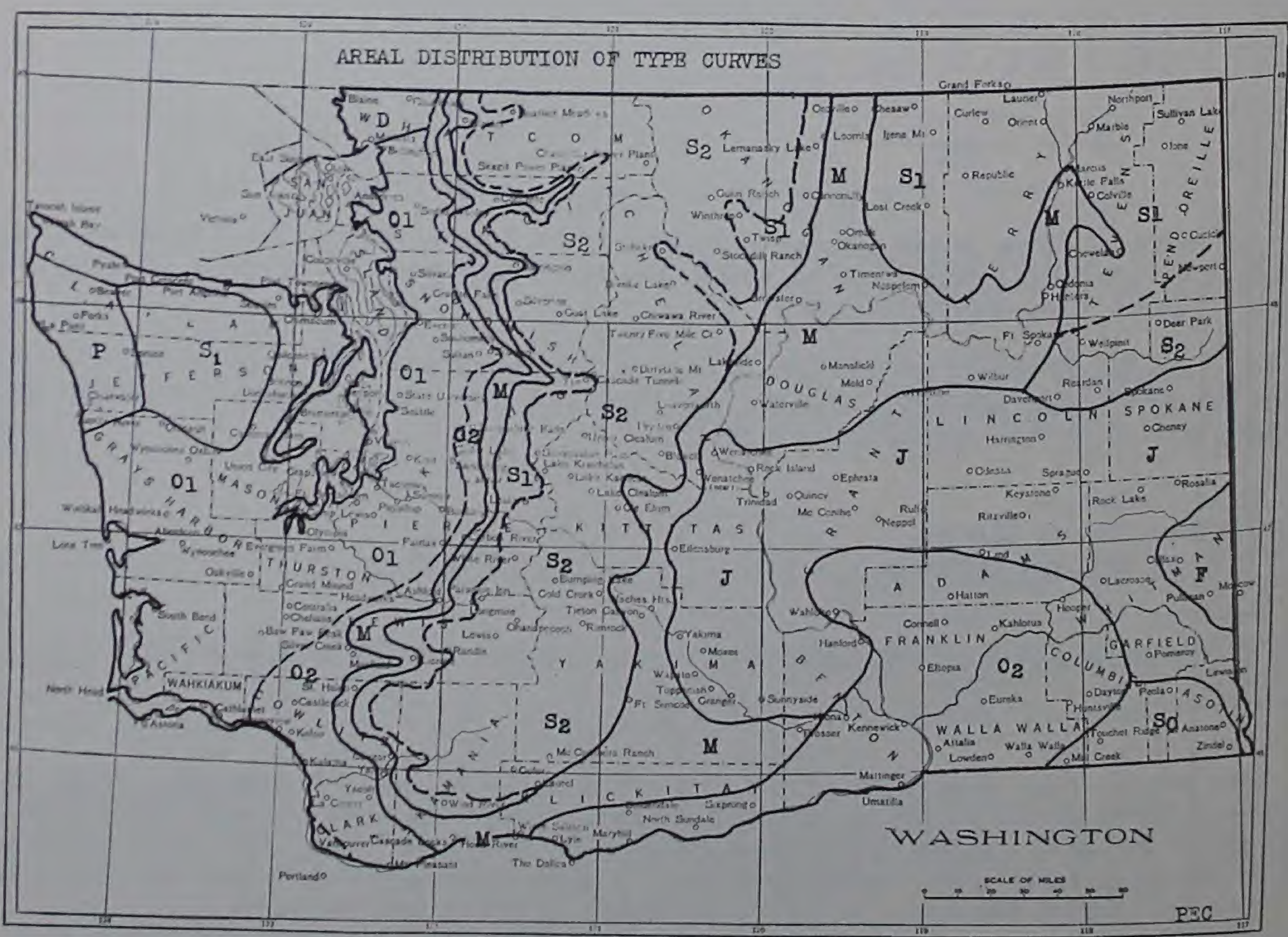

Fig. 1

Table 1--Average depth on ground on 15th and 31st of the month

Station	Altitude, feet	Length of record	October		November		December		January		February		March		April	
			15	31	15	30	15	31	15	31	15	28-29	15	31	15	30
Aberdeen	105	21	0	0	0	0	0.3	0	0	1	0.7	0	0	0	0	0
Anacortes	60	21	0	0	0	0	0.2	0	0.1	0.3	0.1	0	0	0	0	0
Anatone	3790	23	0	0.3	1.3	2	4.5	6.2	8	9	12	11	7	3	1	0
Arlington	500	10	0	0	0	0	0.3	0	0	0.7	0.4	0	0	0	0	0
Attalia	360	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bellingham	107	22	0	0	0	0	0.8	0	0.5	1.3	0.2	0	0	0	0	0
Benton City		20	0	0	0	0.3	0.7	0.5	0.6	0.9	0.7	0	0	0	0	0
Berne	2871	8	0.9	0.5	4.5	7	18	34	46	52	50	44	35	28	8	0
Blaine	57	22	0	0	0	0	0.7	0	0.3	0.1	0.5	0	0	0	0	0
Bremerton	7	20	0	0	0	0	0.1	0.1	0.1	1.7						
Buckley	625	22	0	0	0	0	0.7	0	0.2	1.8	1.2	0	0	0	0	0
Bumping Lake	3400	23	0	0.5	5	6.5	13	24	30.5	38	39	39	36	29.5	19	10
Castle Rock	70	21	0	0	0	0	0.9	0.2	0.5	0.9	0.8	0	0	0	0	0
Cathlamet	340	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cedar Lake	1560	22	0	0	0.2	0.2	4	2	2	7.5	9	4	2.1	2	0.5	0
Centralia	182	21	0	0	0	0	0	0.6	0.7	0	0	0	0	0	0	0
Chewelaw	1668	12	0	0	0.2	0.42	5	6	9	8	4	0.5	0	0	0	0
Chiwawa River	2872	12	0	1.5	14	21	36	63	72	81	84	85	81	72	56	29
Clearbrook	64	23	0	0	0.5	0	2	0.3	0.6	1	0	0	0	0	0	0
Cle Elum	1930	16	0	0	0.5	2	3.5	13	6	10	8	2	0	0	0	0
Colfax	2100	22	0	0	0	0.2	0.7	1.1	1	0.2	2.5	0	0	0	0	0
Colville	1635	21	0	0	1.2	1.1	2.8	5	7	9	8	5.5	2.2	0.1	0	0
Conconully	2285	20	0	0	1.4	2.3	7.7	8	11.2	12.4	11.8	10.6	7.8	2.9	0	0
Concrete	243	14	0	0	1	0	2	2.3	1.5	2.4	2	0.2	0	0	0	0
Cougar	596	19	0	0	0	0.4	3	3.5	7	11	6.8	9.8	10	6.6	4	1
Coupeville	50	19	0	0	0	0	0.3	0	0.2	0.5	0.05	0	0	0	0	0
Cushman Dam	790	11	0	0	0.5	0	0.6	1	2.9	6.4	5.4	4.4	0.6	0	0	0
Darrington	500	23	0	0	3.5	0.2	1.8	4.3	3	7.3	5.4	3.4	1.6	0.4	0	0
Davenport	2450	20	0	0	0.7	1.5	2.2	6	8.5	11.1	12.5	6	2.1	0	0	0
Dayton	1700	20	0	0	0	0.4	0.9	0.8	1.8	2.6	2.3	0.2	0	0	0	0
Destruction I.	64	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diablo Dam	1218	8	0	0	1.5	0.8	3.6	5.5	8.5	9.2	11	6	0.9	0	0	0
Ellensburg	1510	20	0	0	1	0.5	0.7	1.5	0.8	2.5	1.4	0	0	0	0	0
Ephrata	1275	18	0	0	0.4	0.4	1.5	1.9	2.1	3.1	3	0	0	0	0	0
Everett	127	21	0	0	0	0	0.5	0	0.1	0.9	0.4	0	0	0	0	0
Forks	500	20	0	0	0	0	0	0.1	0.5	1.1	T	0	0	0	0	0
Glacier	890	13	0	0	1	0	1.7	1.7	2.4	2.8	3.1	3.7	0.5	1	0	0

Table 1--Average depth on ground on 15th and 31st of the month--Continued

Station	Altitude, feet	Length of record	October 15	October 31	November 15	November 30	December 15	December 31	January 15	January 31	February 15	February 28-29	March 15	March 31	April 15	April 30
Goat Lake	2900	2	0	2	0	5	29	18	25.5	51	50	49.5	53.5	66	16	35
Goldendale	1635	20	0	0	0.2	0.1	0.2	0.2	0	0.9	0.2	0	0	0	0	0
Grapeview	30	19	0	0	0	0	0.15	0	0.1	0.8	0.5	0	0	0	0	0
Guler	1960	17	0	0	1	1.3	4.5	16	17	24	24	20	12	616	2	T
Hanford	385	20	0	0	0.1	0.1	0.7	1.5	0.1	0.2	0.1	0	0	0	0	0
Harrington	2167	20	0	0	0.3	0.8	1.3	3.8	3	4.9	4.6	2.4	0.5	0	0	0
Headworks	985	20	0	0.1	0	0	0.6	0.2	0.3	1.5	8.8	...	...	0.95	0	0
Kahlotus	1000	21	0	0.09	0.25	1.2	0.8	2.2	1.4	3.1	1.3	0.4	0.18	0.1	0.21	0.01
Kalama	300	19	0	0.09	1.8	T	T	1.5	0.4	1.4	4.7	1.4	0.4	T	6.7	0.34
Kelso	500	11	0	0.04	0	0	0.13	0.07	1.6	5.9	0.5	0.49	0.05	0.5	0	0
Kennewick	510	20	0	0.2	1.1	1.5	2.8	4.7	3.8	5.8	3.1	1.4	0.98	0.05	0.14	0
Kent	32	20	0	T	0	0	0.7	0.17	0.3	2.5	2	0.1	0.28	0.1	0.9	0
Kettle Falls	1265	20	0	0.3	1.1	1.4	4.5	7.4	5.9	9.1	4	2.4	1.9	0.1	0.1	0
Keyport	46	17	0	0	0	0	0.38	0.3	0.16	1.4	0.4	0	T	T	0	0
Landsburg	535	20	0	0	0	0	0.014	0.005	0.05	0.8	0.36	0	0	0	0	0
Leavenworth	1167	20	0	0.5	2.1	6.8	11.4	16	13.2	19	9.7	6.2	2.5	6.4	0	0
Lester	1626	9	0	0	2.4	1.8	1.8	6.4	7	10.6	8.1	3	...	0.2	0	0
Longmire	2761	..	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Mt. Baker	4200	11	0.7	4	27	32	52	95	108	121	125	141	148	175	172	141
Naches Height	1874	26	0	0	0.5	1	1.7	4.3	3.7	5	3.2	0.5	0	0	0	0
Newport	2135	21	0	0.3	0.5	0.7	3	6	6.8	9.5	9.9	4.4	2.5	0	0	0
Northport	1350	12	0	0	0.7	1.7	3.5	6.5	9	12.5	11.5	8.5	3.3	0	0	0
Oakville	85	22	0	0	0	0	T	0	T	1.5	0	0	0	0	0	0
Odessa	1590	28	0	0	0.3	0.3	1.5	1.5	1.5	2.2	1	0.2	0	0	0	0
Okanogan	910	12	0	0	0.7	T	0.8	4.1	4.8	5.9	5.7	2	T	0	0	0
Olga	60	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Olympia	69	24	0	0	0	0	0.5	0.2	0.5	1.5	0.2	0	0	0	0	0
Oroville	922	19	0	0	0.1	0.2	0.6	1.9	1.9	2.2	1.7	0.8	0	0	0	0
Paradise Inn	5550	17	3	8	20.5	36	65	87	116	136	144	157	166	184	181	163
Pomeroy	1860	12	0	0	0	T	0.5	0.8	0.8	1.1	0.8	0	0	0	0	0
Port Angeles	29	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Port Townsend	80	23	0	0	0	0	0.3	0	T	0.8	0	0	0	0	0	0
Pullman	2550	22	0	0	T	0.5	1	1.5	2.5	4	6	3	T	0	0	0
Quilcene	30	17	0	0	0	0	T	0	T	0.5	0.2	0	0	0	0	0
Quinault	300	20	0	0	0	0	T	0	0.4	1.2	0.5	0	0	0	0	0
Republic	2650	20	0	T	1.5	1.5	3.8	616	10.2	9.6	8.3	6.6	3.6	18	0	0
Rimrock	2730	20	0	T	1.6	3.1	5.2	10.6	11.5	19:7	15	10.5	4.8	1.2	0	0

Table 1--Average depth on ground on 15th and 31st of the month--Concluded

Station	Altitude, feet	Length of record	October		November		December		January		February		March		April	
			15	31	15	30	15	31	15	31	15	28-29	15	31	15	30
Ritzville	1625	21	0	0	0	0.4	0.9	1.3	1.7	3.5	2.7	0.5	0	0	0	0
Rosalia	2425	21	0	0	T	0.9	1.9	2.3	2.6	4.8	4.6	16	0	0	0	0
Seattle (U.W.)	160	20	0	0	0	0	0.7	0	T	0.5	0.5	0	0	0	0	0
Sedro Wooley	48	20	0	0	0	0	0.3	0	0	0.8	T	0	0	0	0	0
Sequim	187	20	0	0	0	0	0.3	T	0.3	0.4	0	0	0	0	0	0
Silverton	1511	7	0	0.6	2.5	4.2	10	24.3	36.5	39	48	48	46	46	34	25
Sixprong	1100	20	0	0	0	0	1.1	0.8	0.5	2.1	1.4	0	0	0	0	0
Skagit Power Plant	505	13	0	0	0.3	3	3.8	3.5	2.6	2	2.2	2.1	0	0	0	0
Snoqualmie Pass	3010	17	T	4.5	10.5	15	31	48	66	79	90	92	91	92	71	50
Snoqualmie Falls	430	20	0	0	0	0	0.7	T	0.2	1.2	0.3	0	0	0	0	0
Snyder's Ranch (Stockdill)	2200	20	0	T	2.2	5.5	11.3	19.4	22	26.2	26.4	24.3	16.4	5.9	0.33	0
South Bend	140	21	0	0	0	0	T	0	T	T	0	0	0	0	0	0
Spokane	1929	14	0	0	0.3	0.1	0.1	0.2	1.2	1.9	1.1	0	0	0	0	0
Spruce	300	12	0	0	0	0	0.5	1.1	2.2	5.2	5	2	0	0	0	0
Stampede	2777	16	0	0	3.3	5.3	16.9	21.9	31.3	40.4	41.5	36.9	30	11.1	8.5	1.7
Startup	560	13	0	0	0	0	0.7	0	1.3	2.1	13	0	0	0	0	0
Stehekin	1140	20	0	0	0.8	1.9	10.7	16.7	25.1	31	31.7	24	19	7.7	0	0
Sunnyside	740	20	0	0	0	0	0.6	0.8	0.8	1.2	0.5	0	0	0	0	0
Tacoma	194	17	0	0	0	0.2	0.2	0.3	0.2	1.1	0.6	0.1	0	0.09	0	0
Tye	3126	11	0	0.5	5.9	8.8	20.1	17.8	36.7	48	49.3	46.5	55.3	45.5	26.4	10.5
Vancouver	115	18	0	0	0	0	0.9	0	0.9	1.2	0.4	0	0	0	0	0
Wahluke	416	22	0	0	0	0	0.6	0.1	0.2	0.5	0.1	0	0	0	0	0
Walla Walla	991	20	0	0	T	0.27	1.5	1.3	0.87	2.8	2.1	0.18	0	T	0	0
Waterville	2675	20	0	0	1.5	1.4	2.7	5.2	5.7	9.3	6.4	4	1.2	0	0	0
Wellpinit	2450	14	0	0	1	1.2	2.5	8	9.5	10.5	9.5	5.4	1	0	0	0
Wenatchee	2200	19	0	0	0.3	0.6	2.5	3.9	3.7	4.2	3.2	0.8	0	0	0	0
White Salmon	1700	21	0	0	0.5	0.7	2.3	8.1	6	9.5	4.8	2.5	T	0	0	0
Wilbur	2178	20	0	0	0	0	0.1	0.7	0	0.4	0.7	0.5	0	0	0	0
Wind River	1138	21	0	0	0	0	3.9	6.5	8.5	12.1	15	10.4	6.1	2.1	0.2	0
Winthrop	1765	18	0	T	1.8	3.1	7.8	11.8	15.1	17.5	16.5	12.5	5.4	0.5	0	0
Yacolt	737	17	0	0	0	1.3	1.2	0.4	0.7	1.9	1	0.3	0	0	0	0
Yakima	1071	14	0	0	T	0.8	0.4	1.5	1.4	0.4	0.2	T	0	0	0	0
Yale	375	2	0	0	0	0	0	0	0	5.5	0.25	4.5	1.3	0	0	0

Table 2--Main and subtype curves representative of snowfall, State of Washington

Type		Duration(weeks)		Altitude, feet	Criteria	Location
Main	Sub.	Min.	Max.			
D	..	..	5	0-500	Maximum depth on ground occurs on Dec. 15; cover not continuous during winter	North of Bellingham
O	1	1	5	0-500	Maximum depth on ground occurs on Jan. 31; cover not continuous during winter; greater depth on ground on Dec. 15 than Dec. 31	West of Cascades in Puget Trough
O	2	5	10	500-1,000	Maximum depth on ground occurs on Jan. 31; greater depth on ground on Dec. 15 than Dec. 31; depth on ground on Dec. 15 less than 1.0 inch	Narrow belt west of Cascades between approx. 400 and 800 feet; lowest part of Inland Empire around confluence of Columbia and Snake rivers
P	..	0	10	0-1,000	Continuous cover; gradual increase in depth to maximum on Jan. 31; maximum depth less than 10 inches	Southwest slope of Olympics to Pacific Ocean
J	..	10	20	1,000-2,500	Maximum depth on ground occurs on Jan. 31; maximum depth less than 10 inches; cover is continuous during winter	Much of Inland Empire
M	..	15	20	600-1,500 (west side of Cascades) 1,500-3,000 (east side of Cascades)	Maximum depth on ground on Jan. 31; depth on that date less than 10 inches; depth on Dec. 31 either greater than that of Jan. 15 or nearly equal to it; continuous cover	Narrow belt on west side of Cascades; wide belt between S_2 and J east of Cascades
F	..	15	20	1,500-2,500	Maximum depth on ground occurs on Feb. 15; depth on that date less than 10 inches	Palouse Hills
S	0	More than 20	..	Above 2,500	Maximum depth on ground occurs on Feb. 15; depth on that date greater than 10 inches; constant rate of increase in depth to maximum depth	Blue Mountains
S	1	More than 20	..	Above 2,500	Maximum depth on ground occurs on any date between Jan. 31 and March 15; maximum rate of increase in depth occurs between Dec. 15 and 31; another rapid increase in depth occurs between Jan. 15 and 31; maximum depth on ground more than 10 inches	Intermediate slopes of Cascades; Okanogan Highland; Olympic Mountains
S	2	More than 20	..	Above 3,000	Maximum depth on ground occurs on any date between Jan. 31 and March 15; maximum depth on ground more than 10 inches; maximum rate of increase in depth occurs between Nov. 30 and Dec. 15 or between Dec. 31 and Jan. 15	Higher parts of Cascades; southern portion of Okanogan Highlands just north of Spokane

A thorough analysis of the contribution of each control to the curves of the various types is undoubtedly a problem of major research in itself. Some features of some curves, however, have causes which are more or less obvious and may be worthy of note.

O_1-curve--The small amount of snow on the ground at any one time is the result of the low altitude, and the rainy polar Pacific air, which prevails during at least 80 per cent of the time [8], from off the warm (for the season) Pacific. Within the altitudinal limits and the location of area having this type of curve no month has an average temperature below the freezing point. Such temperatures militate against the precipitation being in the form of snow and prevent the accumulation of such snow that does fall. The mountain barriers effectively block all but a few flows of cold polar continental air from reaching this area, but when this air-mass arrives (from the east or northeast) it is cold enough to produce snow from the polar Pacific air which it lifts. This condition may happen some half-dozen times during a winter; when it occurs the temperature is low enough to preserve the snow-cover that has preceded it. These flows are most frequent in January and early February and hence account for the snow on the ground at that time. However, a snow-cover has been observed on the ground only four to six times in the past 20 years at the middle of January and only slightly more frequent on the last of the month.

The cause of the snow-cover in mid-December is the same as that in January and February, but it is more difficult to ascribe the depth on the ground in the forepart of December to more frequent flows of polar air than at the end of the month. This, however, appears to be the case. It is likely that the increased circulation in early December is sufficient to allow better southwestward spread of polar air behind a passing depression. Further, it is likely that the westward flows of polar air are more frequent in January than in late December because of the greater volume and stronger pressure-gradient of the polar air. Whatever the causes may be, it remains that snow has been observed on the ground as many times in mid-December as in mid-January, but none on the ground at the end of December.

The average amount of precipitation per day for Seattle in December offers a clue to this point. During this, the rainiest month, the average for the first 15 days is 0.1846 inch (50-year record ending in 1927), whereas for the last half it is 0.1756 inch. The maximum daily amount during the month falls during the six days preceding the 15th, from the 9th through the 14th, and averages 0.2033 inch.

O_2-curve--The location of this sub-type is directly dependent on altitude and the relation to the sea-level gap of the Columbia River. West of the Cascades this sub-type is at an altitude high enough to prevent the complete melting of any snow that falls in December, particularly any that falls in the latter half-month. Nevertheless, there is an average depth on the ground of less than one inch at the end of the year. To the east of the Columbia gap the area having this curve is not above 1,000 feet high. By reason of this low altitude and the more or less easy access of the polar Pacific air through the river-gap, even the average January temperatures are above freezing. Therefore, it is expected that the snow-cover would be thin. Again, the snow is largely the result of lifting caused by polar continental air and not from the topography or from snow being carried over the mountains.

D-curve--This is similar in homology to the O-curve except that the maximum depth comes in mid-December. The area having this type is influenced by the cold air which drains, intermittently, from the upper Fraser Valley through the narrow, low gap to the northeast. By mid-December the Fraser Valley north of the gap has a snow-cover and sub-zero temperatures are common. Pressure-gradients favorable to the movement of this cold air to southwestward through the gap seem to be more frequent in early December than later. The volume of this cold air coming through the gap is sufficient to flood only the lower Fraser Valley; this cold air seldom extends as far south as Bellingham.

P-curve--Below approximately 1,000 feet to the west of the Olympics is a small area which has a short but continuous snow-cover, the depth of which is dependent largely on altitude or distance from the coast. As is true for both the D- and O-curves the cause of snow is from the lifting of polar Pacific air by the stable, cold polar continental air. The circuitous route that the initial part of the cold, stable air must take over the warm surface of the Puget Trough to reach this area permits the mid-December flows to have temperatures too high for snow at that time. Later in the season this condition does not obtain and snow may fall and remain on the ground for a short time.

M-curve--This type of curve, like the O_2, is found both west and east of the Cascades. The main characteristic of this type is that the maximum amount on the ground is between five and

ten inches; the determining control is altitude, the area with this type of curve is higher than that occupied by the O_2, and on the west slope of the Cascades the type occupies a narrow belt because of the abrupt rise of the mountains.

At this intermediate altitude the greatest increase of depth comes during the latter half of December, after which the cover remains almost constant in depth, or may even decrease, until mid-January. Between mid-January and the last of the month there is increase in depth, but not as rapid as that in the latter half of December. The shape of this curve suggests that it is not cold enough to permit accumulation during the first half of December, but it is cold enough during the latter half. During the latter half of January and all of February the increase and decrease in depth is more nearly the normal snowfall-curve to be expected with temperatures at or just below the freezing point. Settling is sufficient with a cover as deep as that present at the end of December to partially nullify the increase that would be expected from the amount that falls in the forepart of January.

The area where this type of curve is present on the east flank of the Cascades is indicative of the main cause. Most of the snow has been formed by the ascent of the air up the west slope and has been carried over the mountains. Though the amount that would be carried as far east as this area is small compared to that formed on the west slope during the ascent of the air, winter temperatures are low enough to prevent melting of that which falls. Nevertheless, considerable loss must take place by sublimation into the dry air. Some snow is caused by the westward and southern motion of polar continental air, but the amount is not considerable because the maritime air which would be lifted by polar continental air has already lost most of its moisture in crossing the Cascades. The altitude, of course, plays an important rôle, too. This type of curve is found at a somewhat lower altitude on the west side than on the east side. Here it is between 3,000 and 4,500 feet below the general crest of the mountains to windward. This places its altitudinal zonation between 1,500 and 3,000 feet above sea-level.

J-curve--The M-type gradually merges into the J-type. This type also has a definite altitudinal zonation but is found only on the east side of the mountains. Above 1,000 feet the temperatures average below freezing for the winter months so there is little melting during the period when the depth on the ground is increasing. West of Ephrata the snow is mainly "carry-over", as is true for the M-curve, but because the surface is lower and farther from the Cascades than the M-type, there is less snow (maximum does not exceed five inches). As the altitude of the "Inland Empire" increases east of Ephrata toward the mountains of Idaho, this rise is reflected in a deeper snow-cover, which is almost five inches at Rosalia by the end of January, and points to an increasing contribution to the total depth on the ground by southerly and southwesterly air ascending in response to the topography. There is probably little "carry-over" from the Cascades at the eastern portion of this area.

F-curve--This type is similar in most respects to the J-type except that the maximum depth comes in mid-February and not at the end of January. No explanation for this fact is attempted at present.

S_0-curve--This type is found only in the Blue Mountains (Anatone) where the depth on the ground increases slowly but steadily from mid-November to mid-February to a maximum of more than ten inches. The most rapid increase in depth comes between the last of January and mid-February, a feature which is found at some other mountain stations.

S_1-curve--On the intermediate slopes above the M-type on the west side of the Cascades between the approximate altitudes of 1,500 and 2,500 feet is the S_1-type. Its curve is distinctive from that found at higher altitudes in that the maximum increase of depth occurs between the end of November and mid-December. Here the greatest accumulation comes two weeks prior to that of the M-type some several hundred feet lower and that of the higher altitudes (S_2) also. Undoubtedly, it is the temperature which controls this relationship. It has been suggested that the rapid increase of depth in the M-type in the latter half of December was because temperatures permitted such. This again holds true for the S_1-type where freezing is the average condition in the forepart of December. This is followed by slower accumulation for the next two weeks during the period when the M-type increase was greatest. However, at this time the actual increase of depth on the ground for the S_1-type may be much more than that of the M-type.

Most of the stations experience another rapid increase of depth during the first two weeks of January which is followed by slower accumulation until the maximum is finally reached. By mid-January the cover is so deep that settling, and other processes which decrease the depth, more or less approach the rate of fall of snow. Therefore, after the early January spurt, the

depth increases slowly to the maximum, the date of which is governed largely by altitude and exposure.

A number of stations show this same type to be present in a fairly wide belt to the east of the broadest part of the Cascades. South of Lake Chelan the slope of the mountains is too steep at the altitude of this type to detect its presence though theoretically it should be present along the eastern flank of the Cascades. Nearly all of the Okanogan Highlands is within the altitudinal range for this curve and consequently this type is wide-spread there.

As with the M-type the cause of the snow on the east side of the Cascades is primarily from "carryover" with a secondary contribution from the southwest movement of fronts along polar continental air-masses. West of the mountains the snow is the result of the southwest wind rising over the mountains.

S_2-curve--Above approximately 2,000 to 2,500 feet on the west side up to the general crest and for some distance to the lee (east) of the top of the Cascades this type prevails. This type is distinctive from the S_1 sub-type because the greatest build-up of depth occurs between December 15 and 31 when there is but little increase of depth in the zone below, when there are more days with snow falling, when there are fewest clear, cold days and before the depth on the ground is sufficiently thick for active settling to take place. Between December 15 and 31 all stations in this type on the west slope report an average increase of depth of more than 15 inches. To the east of the general crest of the mountains there is less increase in actual depth.

The date of the maximum depth varies considerably. A few stations, all to the east of the Cascades, witness the maximum depth on the last of January. On the crest and west slope there is a general retardation of the greatest depth to as late as the end of March for the highest and snowiest places. The lower stations attain their maximum depth in mid-February or early March.

North and west of Spokane several stations (Wellpinet, Newport, Davenport) report maximum depths of slightly more than ten inches with the maximum rate of increase coming during the latter half of December. This may be explained by reason of the ascending air from the southwest and less polar continental air at this time.

Variability of annual snowfall--A number of stations have reliable records for about 40 years or more which can be used to show the variability of amount from year to year. By comparing the graphs of the seasonal totals it is possible to determine whether the same variations take place over the State as a whole or only in sections. Consequently, the total fall was graphed for Seattle (1892-93 to 1938-39), Tacoma (1896-97 to 1938-39), Pullman (1893-94 to 1937-38), Walla Walla (1887-88 to 1934-35), Cle Elum (1899-1900 to 1938-39), Waterville (1893-94 to 1936-37 with 1913-14 missing), Sunnyside (1894-95 to 1936-37 with 1907-08 missing), and Paradise Inn (1919-20 to 1938-39). Each of the above graphs was compared to that of Seattle and Paradise Inn to determine if there was pronounced variability in the same direction from season to season. In the main there was fair correspondence of most of the curves with that of Seattle. Of the 41 years compared, 38 showed a similar trend of more or less snow at Tacoma, Walla Walla had 34 similarities and 7 opposites, Pullman had 22 to 21, Cle Elum 28 to 9, Sunnyside 30 to 9, Waterville 26 to 14, and Paradise Inn had 15 to 4. From these figures it is clear that poorer agreement in trend of amount is not entirely in proportion to the distance from Seattle. Some of these factors have been pointed out in the discussion of causes of the type-curves.

A snowy winter does not mean that the whole State will have more than the normal amount, but the whole of the western lowland and the lower portion of the Columbia Basin (the O_1- and O_2-types) show remarkable similarity of the year by year trend. Most of the area east of the Cascades, except that just noted, also oscillates in the same direction. Only in the seasons of 1903-04, 1906-07, and 1915-16 was there general agreement of more than normal snow over the whole State. The 1922-23 season saw an exceptionally large amount fall in western Washington, but was a poor season east of the mountains. Just the reverse was true in 1931-32.

Standard deviations and coefficients of variation of the annual snowfall for all stations have been computed back to the season of 1917-18. Though some of the stations do not have a 20-year record, yet all fit quite harmoniously in amount of deviation and percentage of variation with stations nearby having a long record. The standard deviation and coefficient of variation for the stations are given in Table 3. Figure 2 shows the isopleth arrangement of the coefficients. It is to be noted that those areas having the P-, D-, O_1-, and O_2-type of curve,

Table 3--Standard deviations

No.	Stations	No. years	Average	σ	σ, per cent	Type curve
1	Aberdeen	21	10.3	11.3	110	O_1
2	Anacortes	21	3.	3.8	126	O_1
3	Anatone	23	82.5	46.	56	S_0
4	Arlington	10	11.2	9.8	87	O_1
5	Attalia	7	8.4	7.4	88	O_2
6	Bellingham	22	11.1	9.	81	O_1
7	Benton City	20	9.7	7.8	80	O_2
8	Berne	8	281.9	80.7	28	S_2
9	Bickleton	6	192.	69.8	35	S_2
10	Blaine	22	11.1	9.1	81	D
11	Bremerton	20	7.8	7.8	100	O_1
12	Buckley	22	13.2	10.1	76	O_1
13	Bumping Lake	23	186.	73.5	39	S_2
14	Castle Rock	21	9.7	8.3	86	O_2
15	Cathlamet	11	0.08	1.18	147	O_2
16	Cedar Lake	22	68.5	39.8	58	S_1
17	Centralia	20	6.5	7.0	108	O_1
18	Chewelaw	12	40.5	21.5	53	M
19	Chiwawa River	12	358.6	81.8	22	S_2
20	Clearbrook	23	15.7	11.5	73	D
21	Cle Elum	20	78.3	25.02	32	S_2
22	Colfax	22	24.2	14.3	58	F
23	Colville	23	40.	11.1	28	S_1
24	Conconully	20	48.	18.4	38	S_1
25	Concrete	14	25.2	18.3	72	M
26	Cougar	19	32.3	47.8	148	M
27	Coupeville	19	4.1	5.	121	O_1
28	Cushman Dam	11	41.	32.9	80	O_1
29	Darrington	23	30.8	29.	96	M
30	Davenport	20	43.	20.	46	S_2
31	Dayton	20	23	14.3	60	O_2
32	Destruction Island	3	4	3.4	85	..
33	Diablo Dam	8	76.5	15.5	19	S_2
34	Ellensburg	20	29.	13.6	44	J
35	Ephrata	18	17.4	9.	52	J
36	Everett	21	11.7	11.1	94	O_1
37	Forks	20	10.	11.7	117	P
38	Glacier	13	41.6	27.3	65	M
39	Goat Lake	2	309.5	18.8	5	S_1
40	Goldendale	20	20.	10.8	53	O_2
41	Grapeview	19	6.	6.4	104	O_1
42	Guler	17	91.8	16.5	17	S_1
43	Hanford	20	12.	6.8	54	J
44	Harrington	20	29.5	18.1	61	J
45	Headworks	20	15.	9.7	63	O_2
46	Kahlotus	21	12.	23.	191	O_2
47	Kalama	19	10.8	9.9	91	O_2
48	Kelso	11	10.	13.8	139	O_2
49	Kennewick	20	24.2	39.9	164	O_2
50	Kent	20	6.8	6.8	100	O_1
51	Kettle Falls	20	28.5	14.0	37	M
52	Keyport	17	3.29	11.3	343	O_1
53	Landsburg	20	3.	3.8	135	O_1
54	Leavenworth	20	95.	24.6	26	S_1
55	Lester	9	70.	13.7	19	S_2
56	Mount Baker	11	494.	87.5	27	S_2
57	Naches Height	26	35.3	14.7	42	M
58	Newport	21	54.8	27.8	50	S_2
59	Northport	12	58.	14.7	25	S_1
60	Oakville	22	8.4	8	95	O_1
61	Odessa	28	20.8	10.2	49	J

Table 3--Standard deviations--Concluded

No.	Stations	No. years	Average	σ	σ, per cent	Type curve
62	Okanogan	12	27.3	11.7	42	M
63	Olga	13	6.84	3.6	52	O_1
64	Olympia	24	11.12	9.2	82	O_1
65	Oroville	19	17.3	10.7	62	J
66	Paradise Inn	17	559	162.4	28	S_2
67	Pomeroy	12	18.83	11.3	60	J
68	Port Angeles	5	9.8	4.3	43	O_1
69	Port Townsend	23	7.	11.2	160	O_1
70	Pullman	22	42.4	19.7	46	F
71	Quilcene	17	8.2	9.2	112	O_1
72	Quinault	20	9.7	11.9	120	O_1
73	Republic	20	48.1	18.	37	S_1
74	Rimrock	20	100	33.7	34	S_2
75	Ritzville	21	13.4	6.7	50	J
76	Rosalia	21	28.9	10.3	35	J
77	Seattle (U. of W.)	20	5.35	8	149	O_1
78	Sedro-Wooley	20	3.6	3.8	105	O_1
79	Sequim	20	7.	8.7	124	O_1
80	Silverton	7	235.	70.1	29	S_2
81	Sixprong	20	15.	11.7	78	O_2
82	Skagit Power Plant	13	52.	35.8	68	M
83	Snoqualmie Falls	20	15.3	13.6	88	O_2
84	Snoqualmie Pass	17	388.	89.5	22	S_2
85	Snyder's Ranch	20	100.7	31.8	31	S_2
86	South Bend	21	4.17	4.3	104	O_1
87	Spokane	14	31.5	12.	38	J
88	Spruce	12	10.7	8.7	81	P
89	Stampede	16	188.	58.1	30	S_1
90	Startup	13	15.9	11.8	74	O_1
91	Stehekin	20	118.	31.4	26	S_1
92	Sunnyside	20	13.	7.8	60	J
93	Tacoma	17	10.7	9.8	91	O_1
94	Tye	11	264.	96.2	36	S_1
95	Vancouver	18	13	9.7	75	O_1
96	Wahluke	22	10.3	7.9	77	O_2
97	Walla Walla	20	21.7	12.	55	O_1
98	Waterville	20	46.4	11.7	25	M
99	Wenatchee	19	33.2	14.7	44	M
100	White Salmon	21	54.	42.9	79	M
101	Wilbur	20	29.	12.5	43	M
102	Wellpinit	14	26.2	17.8	38	S_2
103	Wind River	21	89.2	59.9	67	S_1
104	Winthrop	18	68.7	22.6	32	S_1
105	Yacolt	17	19.	15.6	82	O_2
106	Yakima	14	20.6	8.4	40	J
107	Yale	2	45.	31.	68	M

where the total seasonal amount is small, have coefficients in excess of 80 per cent, with much of the area included within the closed 100 per cent isopleth. The J-type is largely between the 40 to 60 per cent, the M-type between 40 and 80 per cent, the S_0 about 60 per cent, the S_1 between 30 and 50 per cent, and the S_2 between 20 and 40 per cent.

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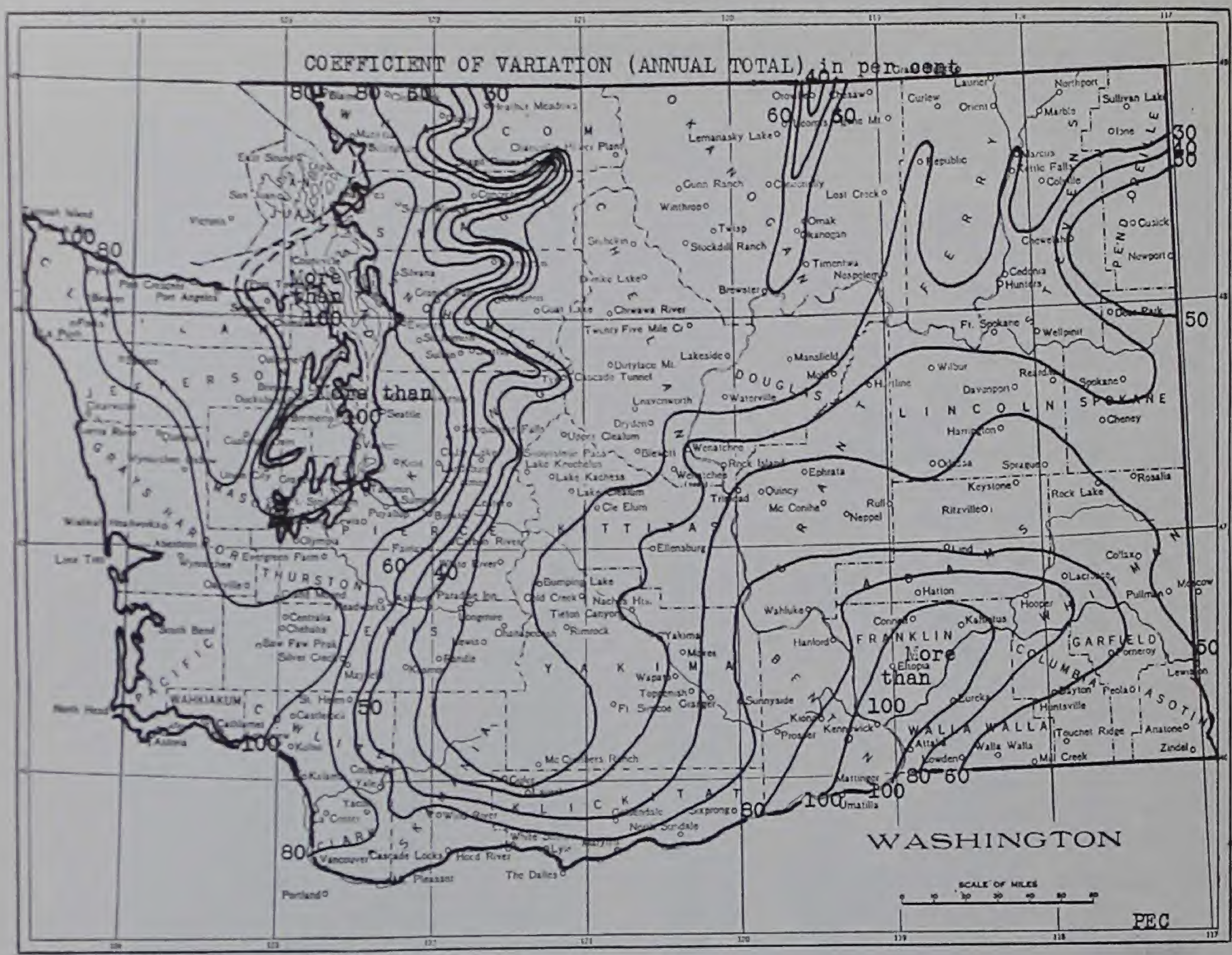

Fig. 2

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THE USE OF SNOW-SURVEY PREDICTIONS IN THE OPERATION OF COMBINED FLOOD-CONTROL AND CONSERVATION RESERVOIRS FOR REGULATION OF SNOW-MELT RUNOFF

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Objectives--This paper illustrates a method developed by the Sacramento District of the United States Engineers for the operation of combined flood-control and conservation reservoirs. It is hoped that the presentation of this procedure will bring forth criticisms and suggestions from other interested parties and agencies. The use of snow-survey predictions in the operation of irrigation or power storage-facilities offers no particular complications. However, in the case of reservoirs which are used for flood-control as well as for irrigation- and power-purposes, the problem becomes considerably more involved. Ideal operation of such multi-purpose reservoirs should result in the following:

(a) The distribution of such waste as may be necessary in the least possible harmful manner, which usually means at the lowest possible rate.

(b) The maintenance of reservoir-releases after the start of snow-melt operation which are

Table 1--Lake Tahoe: Data for plotting of snow-melt runoff versus reservoir release curves
(All values are in thousand acre-feet)

Year	Recorded net inflow for period beginning		Change in storage for releases of 100 c f s	500 c f s	1,000 c f s	1,500 c f s	2,000 c f s	2,500 c f s
1938	April 11	15	13	5	- 5	-15	-25	-35
	21	29	27	19	9	- 1	-11	-21
	May 1	24	22	14	4	- 6	-16	-26
	11	61	59	51	41	31	21	11
	21	59	57	48	37	26	15	4
	June 1	57	55	47	37	27	17	7
	11	36	34	26	16	6		
	21	37	35	27	17	7		
	July 1	9	7	- 1				
	11	10	8	0				
	21	14	12	3				
	Minus net inflow after Aug. 1							
Total net inflow								
	After Apr. 10	351(Σ_1)						
	After May 10	283(Σ_2)						
	After June 10	106(Σ_3)						
Required empty storage								
	On April 11 (Σ_1)		329	239	156	75	1	-60
	On May 11 (Σ_2)		267	201	148	97	53	22
	On June 11 (Σ_3)		96	55	33	13		

adequate for irrigation- and power-needs.

(c) The attainment of the maximum possible reservoir-stage at the end of the snow-melt runoff.

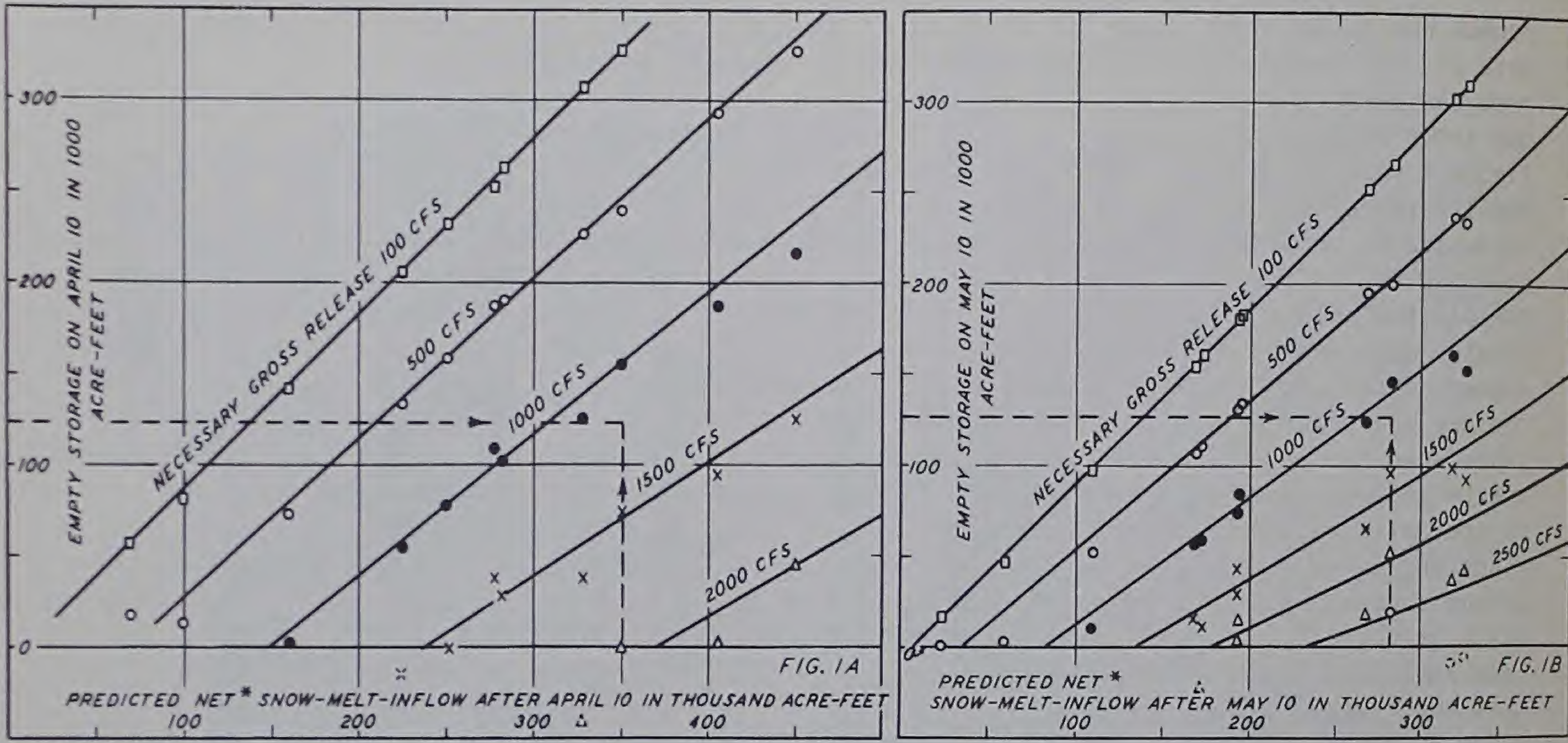
At first thought, it may seem that requirement (b) would automatically be met, and this is normally true in years of excessive snowfall. However, in some instances the reservoir-inflow during the early part of the normal snow-melt period may be less than power-requirements and a premature emptying of the reservoir to provide the required flood-storage would, therefore, result in deficient power-water. In order to determine the release which will satisfy requirements (a) to (c) the following procedure, involving the use of snow-melt runoff versus release curves, has been developed.

Construction of curves--To illustrate the method of constructing the snow-melt runoff versus reservoir release curves the specific case of Lake Tahoe has been chosen. This lake is situated at about elevation 6,225 above mean sea-level, in the Sierra Nevada, in the States of California and Nevada. It is on the headwaters of the Truckee River, the flow of which is used for power-production and irrigation in both the Truckee and Carson River basins. Releases from the Lake into Truckee River are controlled by means of a gated-outlet structure. Snow-surveys in the area tributary to Lake Tahoe are made by the Nevada Cooperative Snow-Surveys under a cooperative agreement with the California State Division of Water Resources. The former organization works up the predictions of net lake inflow (inflow minus evaporation). The steps in developing the curves are as follows:

(a) Commencing with April 11 (the assumed date of availability of earliest accurate prediction) and using actual records of Lake Tahoe stages and releases, a tabulation of mean "ten-day" net inflows is prepared for all flood-years and as many other years of record as may be necessary, as shown for the year 1938 in Column (2) of Table 1.

(b) The changes in storage corresponding to various rates of releases are then tabulated as shown in Columns (3) to (8) of Table 1. The summations of storage-changes after April 10, May 10, and June 10 give the amounts of empty storage required on the respective dates to limit the release to the assumed rate.

(c) Sets of curves are then constructed, assuming various rates of release, as shown on Figure 1, for operation from April 11 to May 10, from May 11 to June 10, and after June 10, by plotting the applicable accumulated net inflow and corresponding required empty storage as abscissa and ordinate, respectively.



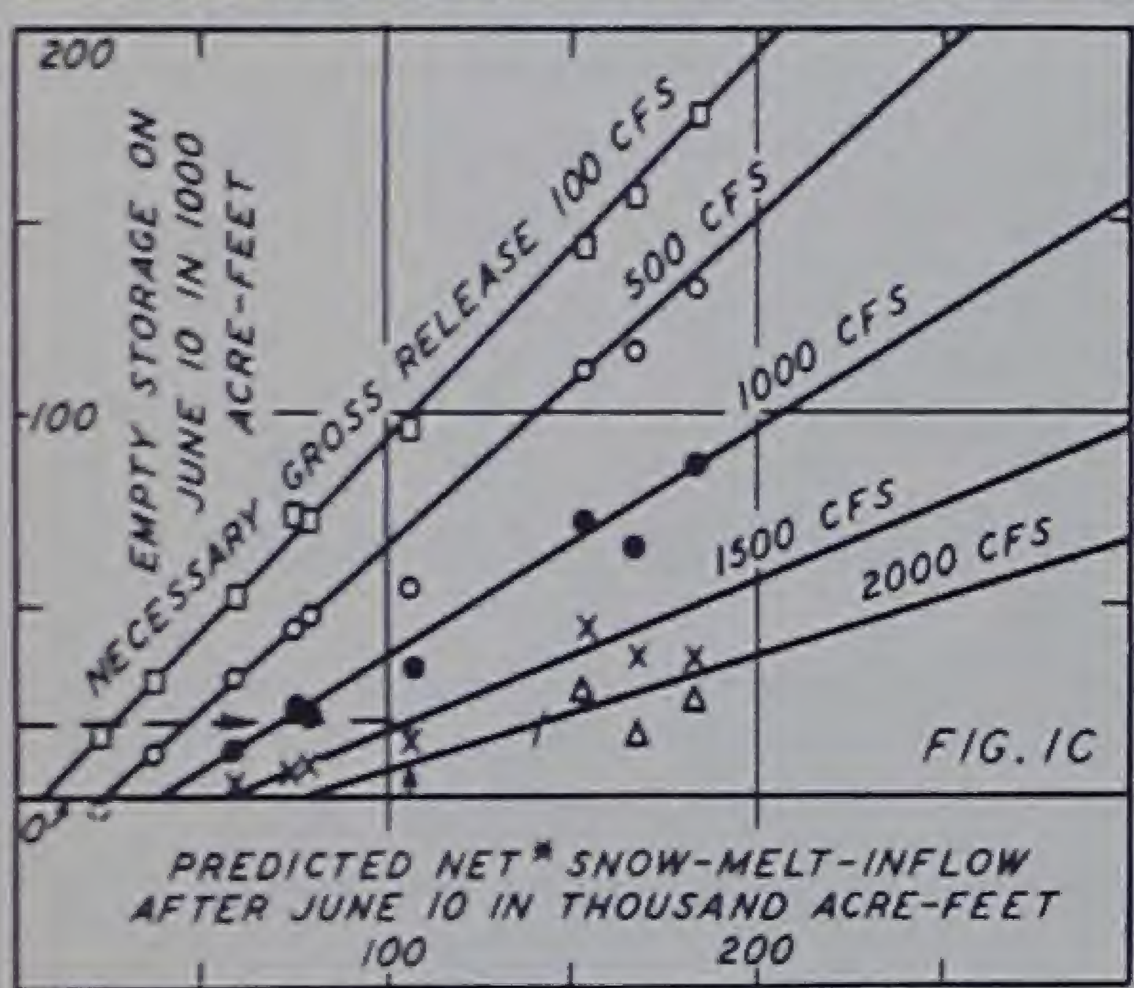


Fig. 1--Lake Tahoe snow-melt runoff versus release curves to guide reservoir-operation during period of snow-melt runoff [*Net = (inflow − evaporation)]

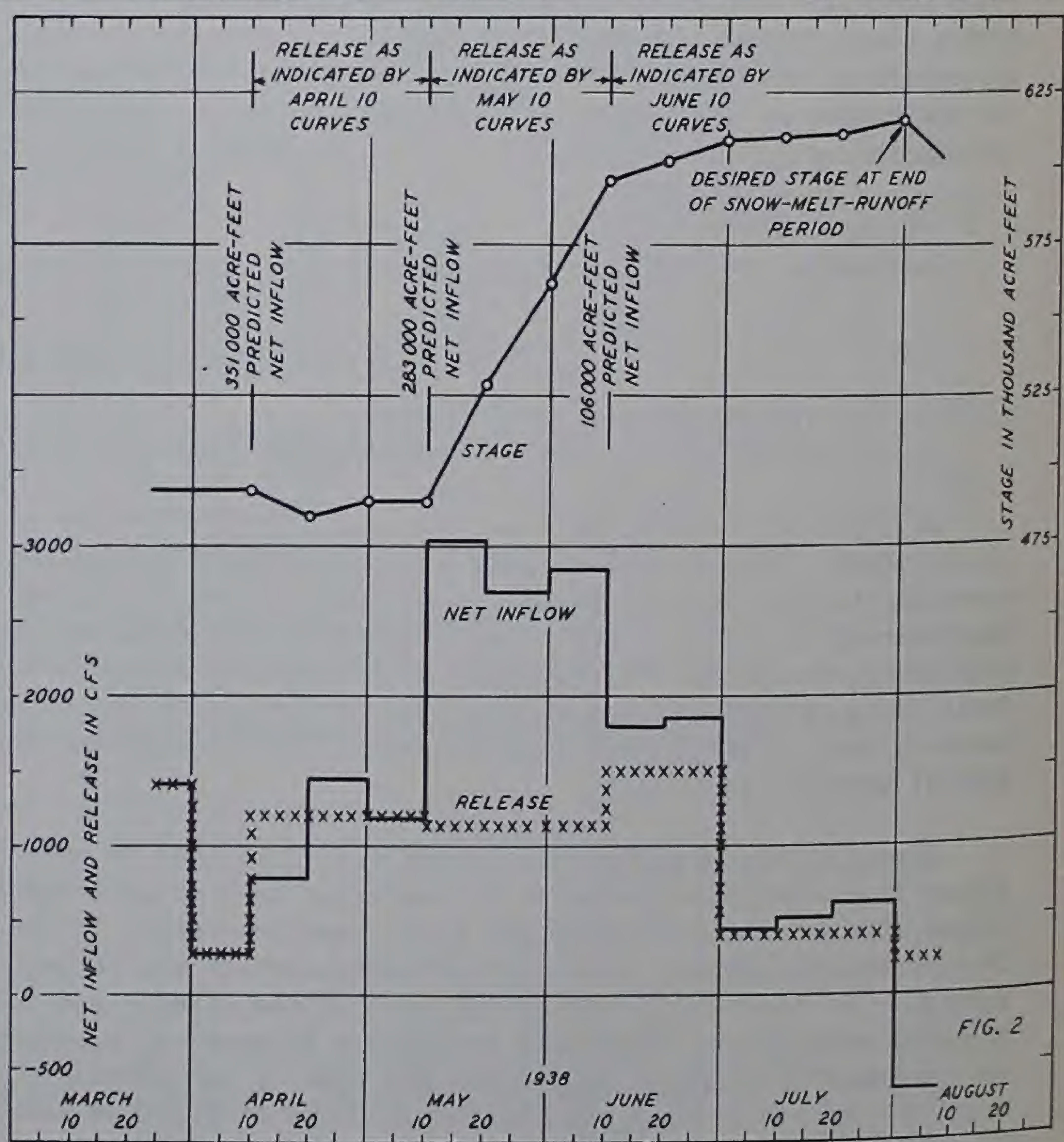


Fig. 2--Hypothetical operation of Lake Tahoe for flood-control and conservation, using snow-melt-runoff versus release-curves

Use of curves--The method of using the curves is simply a reversal of the method of constructing them. Reservoir-operation up to April 10 would be based on criteria for the control of winter rain floods, except that in some cases predictions on March 1 of extremely small or very large snow-melt runoff may warrant storage of a portion of the March runoff, or may require the release of stored water during March, as the case may be. In any event, the release to be maintained after April 10 is determined by entering the first set of curves on Figure 1 with the amount of empty storage on that date and the April 1 snow-survey prediction (adjusted for runoff and precipitation during the first ten days of April). The release is revised on May 11 and June 11 using the appropriate set of curves in the same manner and using in each case the latest snow-survey prediction. The results of the above procedure applied to the year 1938 are shown on Figure 2.

Discussion--The construction of these operation-curves is based on actual recorded snow-melt

runoff while their use is on the basis of snow-survey predictions of runoff. The use of actual data for the construction is necessary because accurate snow-surveys are available for only the past few years and is believed to be justified since predictions are becoming more accurate and any error therein is equally liable to be either positive or negative. It will be noted from Figure 1 that the plotted points for the large releases are more scattered than those for the smaller releases. This is to be expected and merely reflects the variations in pattern of distribution of snow-melt runoff. Where, as in the case of Lake Tahoe, actual records are available for the past 35-40 years, which include both a wet and a dry period, it is probable that the plotted points cover the range of this variation. In drawing the curves through the plotted points, more weight is generally given to the lower points for the smaller releases and to the higher points for the larger releases. This results in safety from a conservation-standpoint in the dry years when flood-control is unnecessary and from a flood-control standpoint in the wet years when the late snow-melt runoff is ample to fill the reservoir. Since the curves as drawn are in general averages of the plotted points, strict adherence throughout the period of runoff to the release indicated by the first set of curves would result in uncontrolled waste in some years and in unnecessary waste in other years. However, by adjusting the release as indicated by the succeeding curves based on later snow-melt predictions, this uncontrolled or unnecessary waste is obviated. In all cases in which these curves have been used so far, the assumption has been made that the first accurate snow-survey prediction would be available about April 11 and that succeeding revised predictions would be at hand about May 11 and June 11. Actually, in years of heavy snow-pack, surveys might be made more frequently and if this were done additional curves could be constructed for operation on the basis of the intermediate predictions and the reservoirs release revised more frequently. In the case of a relatively small reservoir where the variations of inflow during a ten-day period are considerable, the curves may be constructed through the use of mean daily rather than "ten-day" mean inflows.

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SOIL-FREEZING AND FOREST-COVER

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An important though little-investigated problem is the relationship of soil-freezing to forest-cover. With the idea of determining some of the phases of soil-freezing under different cover-conditions, measurements of depth of frost in the ground were undertaken at the Gale River Experimental Forest in northern New Hampshire. In agreement with the exploratory character of this study, no attempt was made to analyze statistically the correlation between the depth of frost in the ground and the individual factors affecting soil-freezing. Any definite trends, however, were noted and additional measurements taken in order to throw some light on the influence of some of the important factors.

The study was initiated in the fall of 1937. On three 0.1-acre plots established in the spruce flat and spruce swamp types and in an open field, measurements of frost-depth were continued for three successive winters. In 1939 two additional plots, one in a fir flat, the other in a northern hardwoods type, were established and measurements continued through the winter of 1939-40. In addition to measurements on these plots, numerous borings were made in surrounding areas differing from the sample areas in drainage and soil-texture. Most of the measurements were taken with a frozen-soil boring tool developed especially for this purpose by B. C. Goodell.

The depth to which frost penetrated the ground under different cover-conditions is presented graphically in Figure 1. Since the results obtained in the fir flat were practically identical to those obtained in the spruce flat, the graph for the former was omitted.

The findings of the investigation are summarized as follows:

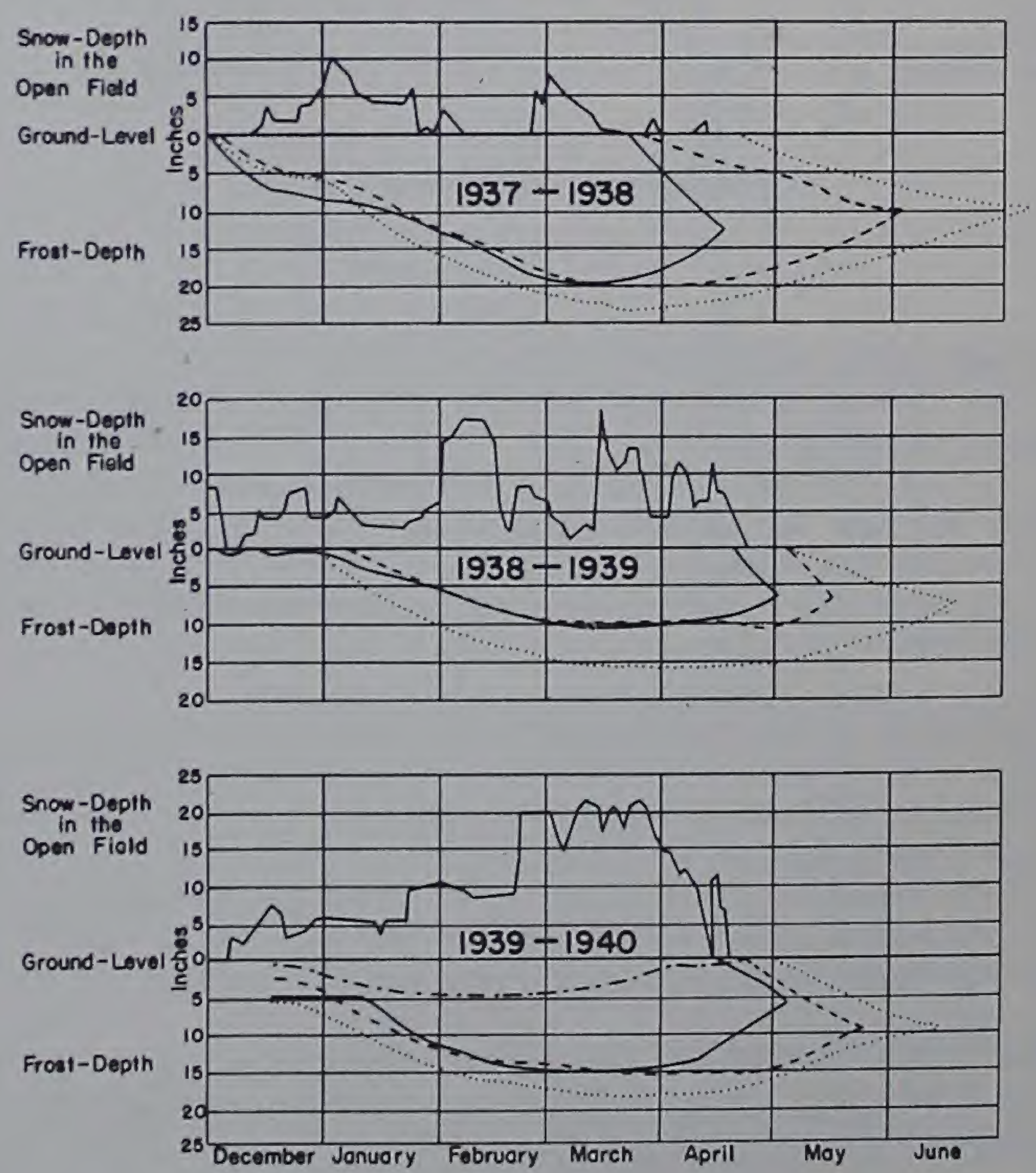
(1) Forest-cover has a favorable effect on early winter floods. Two factors are mainly responsible for this: (a) Delay of ground-freezing prior to snowfall in soils protected by tree-growth; (b) the type of freezing occurring in these soils. Under forest canopies, soils did not begin freezing until continuous low temperatures set in about the beginning of December. Moisture present in the litter, humus, and upper layers of the mineral soil formed snow-like crystals enabling the soil to maintain a good degree of permeability far into the winter. Soils in the open field, on the other hand, began losing their permeability in early November when they began freezing solidly for several days at a time.

Observations made during and after a heavy rain in December of 1937 illustrate the effect of different types of freezing on runoff. Before the rain, freezing in the open field had reached a depth of four inches, in the spruce swamp 2.5 inches, and in the spruce flat 1.5 inches whereas in the open the rain of 1.78 inches thawed only one-fourth to one-half inch of the soil-surface, with no thawing whatsoever occurring on the level portions of the site. Under the forest-canopies most of the frost left the ground. What frozen patches remained in the forest were saturated with freely moving water. In the open field, water remained standing in slight depressions or ran freely along the slope. Under the forest-cover no traces of free water were observed on the surface during or after the rain.

(2) Depth and time of soil-freezing and rapidity of thawing vary with the type of forest-cover. Frost-penetration was least in the hardwood plot, greatest in the spruce swamp. Thawing began and was completed earliest in the hardwood stand. The open field ranked second in this respect, followed by the spruce flat and spruce swamp in the order named. These findings can be largely explained by the varying depths of protective snow-cover accumulated on the plots. Owing to effective interception of snow by dense conifer crowns, only a light mantle of snow covered the forest-floor in spruce-flat and spruce-swamp plots. In the hardwood stand, owing to the open character of the hardwood crowns, snow-cover was as deep as in the open. Another favorable factor characteristic, particularly of hardwood stands, is the presence of last year's dead forest-floor vegetation which tends to enhance the insulating effect of the snow.

(3) Snow-cover affects soil-freezing to such an extent that even slight trampling of the snow, thereby increasing its conductivity, was found to greatly affect the next remeasurement if taken too near the trampled area.

(4) Thawing of the ground from the surface does not begin until the snow has melted; that from the bottom starts somewhat earlier.



Month	TEMPERATURE 1937-38 Mean	1937-38 Av. Min.	1938-39 Mean	1938-39 Av. Min.	1939-40 Mean	1939-40 Av. Min.
November	32	25	33	23	24	16
December	18	9	21	13	20	11
January	15	4	14	4	10	2
February	20	13	20	8	14	5
March	27	17	22	10	22	13
April	42	31	33	24	34	26

LEGEND

——— Open Field
- - - - Spruce Flat
·········· Spruce Swamp
—·—·— Hardwoods

Fig. 1--Depth of ground-frost in different cover-types (Snow-cover and temperature as recorded at the weather station in the open field)

(5) Forest-litter protects the soil from freezing, thus delaying the penetration of the frost.

(6) Under softwood stands, frost remains in the ground longer than in the open or in hardwoods. The effect of this delay in thawing in softwood stands is probably not as serious as might be judged from the graph. Five to ten days (in the swamp even more) before the last vestige of frost has disappeared, small patches with no frost may be found which would provide channels for infiltration of water.

(7) In poorly drained soils, frost penetrates deeper and stays in the ground longer than in soils with better drainage.

(8) Fine-textured soils resemble, in their influence on soil-freezing, poorly drained soils; coarse-textured soils resemble better-drained soils.

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DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--The use of white- and black-bulb thermometers in snow indicates that radiation from the Sun is effective on dark objects to a depth of 18 inches. Is this heat too slight to melt the ground until the snow-cover has completely disappeared? If not, the earth-warmth mentioned by the author as causing earlier melting from below is more potent than that of the Sun through the snow. Could comparative measurements of these two sources of heat be made?

PAUL L. BEAN (Union Water Power Company, Lewiston, Maine, communicated)--From your last letter, I gathered that you might be interested in the determination of frost-line in this country during the winter. To that end I am forwarding to you a copy of Journal of the Maine Water Utilities Association [March, 1940] in which you will find some studies made on frozen ground, which I trust may be of interest to you--especially the following excerpts from Harvey U. Fuller on frost-penetration:

"Gravel is much more responsive to changes in temperature than clay. The first week in March the depths of the frost-line were much the same. Then under the influence of the increasing temperature of the air, the frost went out of the ground in a week while a month was required to melt all the frost in the clay.

"The frost leaves the ground in about half the time that was required for it to go in.

"The accumulated deficiency in degrees below freezing can be found by subtracting the mean temperature for the day from 32° F. A thermometer read each morning and evening at about 8 o'clock and averaged gives the information near enough.

"In the vicinity of Portland, Maine, it is found that any freezing that occurs before the middle of November is not permanent and if records for the winter are begun at that time a satisfactory result will be obtained. The deficiency below freezing each day is to be added to the sum of the deficiencies of the preceding days.

"In the winter of 1917-18 the accumulated deficiency reached 1500° and in the winter of 1936-37 the high point was 170°.

"In the former year the frost was not out of the ground until about May 1 while in the latter year it was out about April 1.

"Loose unpacked snow is well known to be an excellent insulator but in these days of automobiles where snow-plows keep the ground nearly bare and the traffic soon packs any remaining snow to the condition of ice, the insulating properties of the snow are not effective in the roads.

"A chart has been prepared showing the depth of frost with accumulated deficiency of temperature and the time it might be expected finally to leave the ground."

Valuable and accurate information is now available in meeting the problems of frozen water pipes. The general public have difficulty in understanding how one can tell a week ahead the time when their service pipe will be frozen at a given location. If you desire, I will be glad to forward such information as it becomes available.

WALTER T. WILSON (United States Weather Bureau, Washington, D. C.)--The movement of frost in snow and ice is similar in character to that in soil, and the fundamental rules for soil apply.

At the University of Wisconsin during a cold spell, our class was given the problem of determining how soon the water pipes would freeze. To the public's astonishment, the pipes froze at the date determined although milder weather had meantime set in.

PROGRESS TOWARD A RATIONAL PROGRAM OF SNOW-MELT FORECASTING

Merrill Bernard

Recent studies have been encouraging in their promise of an ultimate rational solution of snow-melt-runoff problems associated with the forecasting of irrigation-water supplies. Less encouraging is the obvious lack of pertinent data upon which to base the operation of forecasting methods which would take into account the influence of the heat absorbed by the snow from the blanketing air-mass and that of radiation and condensation. Observational facilities must be provided which will give more accurate knowledge of the water in the snow and the conditions of mantle structure under which snow responds to melting influences. The location of these observational points must be in accord with statistical principles of sampling which will consider variations in basin shape, elevation, and aspect.

The problem of utilizing water in the form of snow is best conceived of as one of conservation by storage, the great snowfields of the mountainous West being considered as vast reservoirs in which the life-sustaining waters are impounded as realistically as is in the case of water reserves held behind man-made dams. In the latter type of conservation the control of release is accomplished through mechanically operated gates and valves; in the former, Nature exercises a thermostatic control of water-deliveries by integrating the factors which are known to provide heat for melting. A principal source of heat is that contained in an air-mass moving over a snow-area. Here heat is transferred to the snow-surface through a continually renewed contact between snow and air occasioned by an active turbulence in the lower layers. Also, that portion of the Sun's heat-energy which penetrates the atmospheric envelope contributes appreciable heat to melting processes.

Man, in the valleys far below his source of water-supply, plans to cope with Nature on two fronts. He must select his crop to suit the climate, the length of growing season and the soil-types characteristic of his valley. He must gage the extent of his planting to the amount of water stored in artificial reservoirs or in the snow lying at the headwaters of his river. If he is so fortunate as to have his water impounded behind a dam he can adjust the delivery of his supply to the operations of planting, cultivating, and harvesting. If his irrigation-water is withheld largely in the form of snow with only limited retention by artificial storage he must adjust these operations to the schedules of delivery which Nature will decide upon. Or if he succeeds in his attempts to husband his supply by carrying over from one year to the next an occasional surplus, he must be able to anticipate Nature's schedule in both amount and rate of release in order that withdrawals may synchronize reasonably with demands of his growing crops.

Points of comparison between artificial and natural storage are summarized in the following table:

ARTIFICIAL STORAGE	NATURAL STORAGE
<u>Measure of amount available</u>--Area-depth relations of the reservoir	<u>Measure of amount available</u>--Area-depth and density relations of the snow-mantle; infiltration-capacity of soils comprising that portion of the basin covered
<u>Factors determining rate of withdrawal measured at point of use</u>--Control-gate adjustment at reservoir; channel-storage and slope-section characteristics of delivery stream	<u>Factors determining rate of withdrawal measured at point of use</u>--Heat transferred to snow from (a) air of lower atmosphere, (b) condensed moisture, (c) underlying soil, (d) warm rain,and (e) radiation; "quality", or degree of ripeness of snow mantle; absorptive capacity of ground-surface; water-loss to the atmosphere from the snow-surface through sublimation and evaporation; retention in natural and artificial reservoirs; channel-storage and slope-section characteristics of delivery stream

Good progress has been made in determining the "duty" of water or the amount necessary to a particular crop to insure a productive maturity. The distribution of this amount throughout the planting, growing, and maturing periods has much to do with the efficacy of irrigation. Fortunate, therefore, is the community whose water-supply is ample and securely held behind an adequately proportioned dam through which withdrawals can be released in specified amounts at any time.

Progress has been made also in determining, through snow-surveys and snow-gages, the

potential water-supply available in the snow-mantle at the beginning of the irrigation-season. The service of gathering these data, now well established in the West, has a high economic value and has made it possible for the valley dweller to compare the potential water-supply for the current season with that of a "normal" year or with a particular year embraced by the period of record. Thus the means are provided for determining the number of acres which can be irrigated with the amount of water on hand.

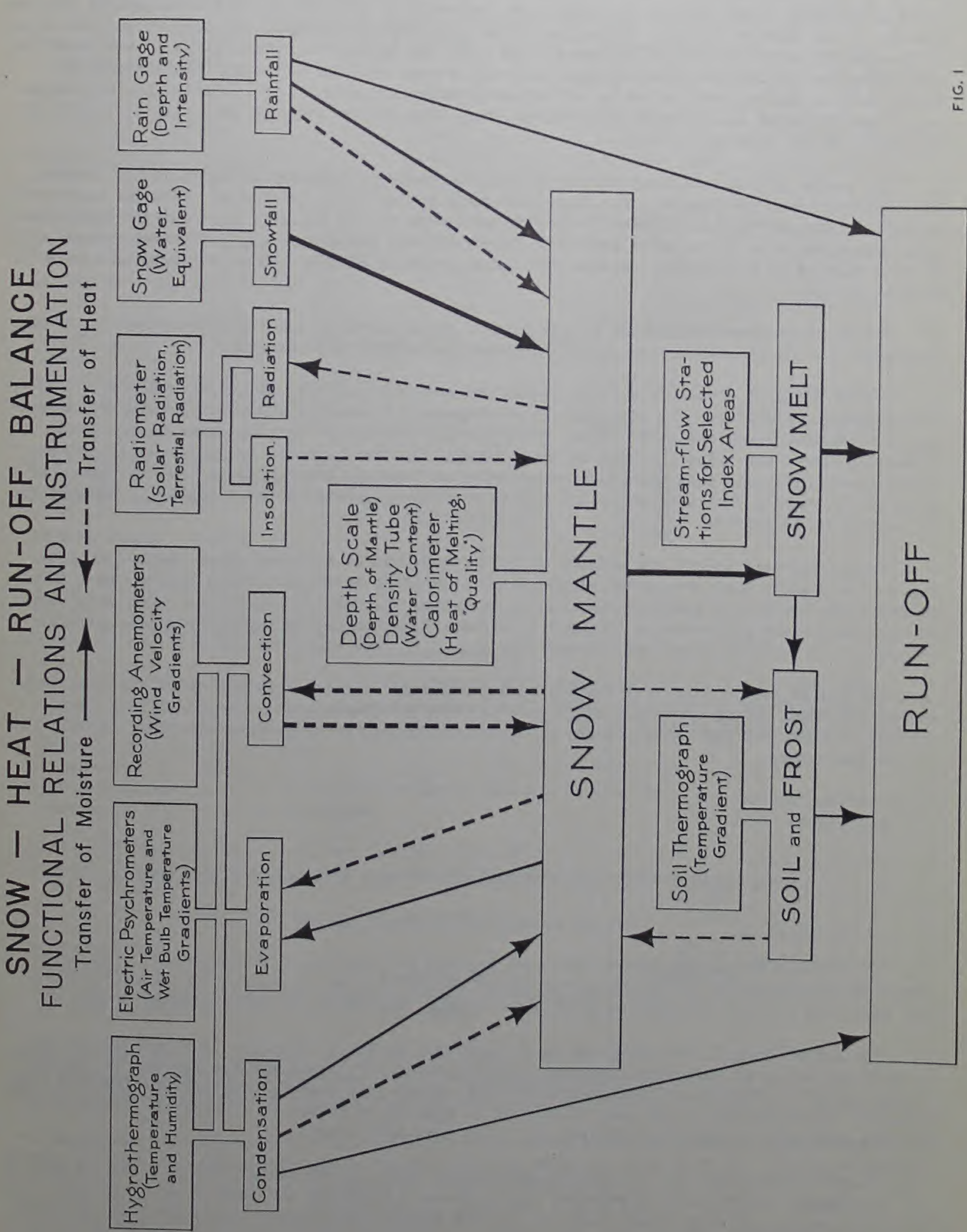

FIG. 1

The cost to store an acre-foot of water artificially varies widely with the demands of economy and the engineering difficulties encountered in constructing the dam and reservoir. In most cases the investment is sufficiently great to account for the largest item of annual cost of the irrigation-operation. It should not be difficult, therefore, to justify the comparatively small expense of providing the facilities which would materially enhance the flexibility of irrigation-operations dependent upon water stored in and released by natural causes from snow-fields at high elevation. In so far as the rate of melting is a function of meteorological factors and their combinations, it would seem desirable to utilize to the fullest extent the resources of the Weather Bureau. These facilities are comprised largely of observational stations throughout the country equipped to measure not only the surface-characteristics of air-masses as they enter and move across the Continent but at a number of them to "sound" the atmospheric column to a height of over ten miles in measuring atmospheric pressure, temperature, and humidity. The number of "radiosonde" stations and the observations taken at each will be materially increased in the future.

The amount of heat reaching the Earth by solar radiation through a transparent atmosphere is theoretically determinable. The degree to which radiation is intercepted by water-vapor and clouds is inherent in the radiometric observations made by the Bureau. In a comparatively short time the Bureau will be prepared to measure directly that portion of the Sun's heat reaching the Earth's surface at a sufficient number of points so that radiation can be included as a forecasting factor.

The mountain snowfall-station of the future, as to function and instrumentation, is shown in Figure 1. All factors are subject to centralized graphic recordation.

The severity of winter climate at elevations sufficiently high to cause heavy falls of snow has accounted largely for the difficulties experienced in securing and maintaining attendance at mountain observational stations. Also, communication facilities for transmission of the observer's reports are either lacking or undependable. Automatic radio transmission of meteorological and hydrologic data has been demonstrated as feasible and the use of such equipment in a modern water-supply forecasting service awaits only the financial support needed to demonstrate its economic utilization.

Within the next decade the science of meteorology can be expected to so improve its forecasting techniques that the period of the forecast will be materially extended and the several elements now dealt with qualitatively can be expressed in quantitative terms. Also to be considered are recent successes in forecasting stream-flow from rainfall which indicate that the problem of forecasting runoff and stream-flow resulting from snow-melt can also be rationalized.

Our objectives in this field should more positively express anticipation of the inevitable demand for water-supply forecasts which have in them the quantitative elements of delivered volumes of water and approximate dates of arrival at points of use; in other words, the forecast of the hydrograph.

U. S. Weather Bureau,
Washington, D. C.

A NEW TECHNIQUE FOR THE DETERMINATION OF HEAT NECESSARY TO MELT SNOW

Merrill Bernard and Walter T. Wilson

The Weather Bureau and others have been engaged for many years in observing the depth and the water-equivalent of fallen snow. Recently, Weather Bureau engineers have devised a method for measuring a third characteristic of snow, namely, the amount of heat required to melt it.

The latent heat of fusion of ice is 80 calories per gram. However, snow is composed not only of ice-crystals, but often includes varying amounts of liquid water suspended in the ice-crystal matrix. The heat of melting of snow may be far less than 80 calories per gram. A quantitative determination of the heat of melting of snow is important in forecasting runoff from melting snow, and in hydrologic design involving snow-melt runoff.

As snow begins to melt, the initial melt-water does not immediately run off, but is held in the snow-mantle. Similarly, a moderate rain, instead of melting the snow on which it falls, may be stored in it. In such cases, very little warm weather may produce disproportionately severe rates of runoff from melting snow. The ratio of heat of melting of snow, in cal/gr to the 80

U.S. DEPARTMENT OF COMMERCE WEATHER BUREAU

MEASUREMENT OF SNOW-QUALITY

Station__________ State__________ Basin__________
Observer__________ Date__________ Hour__________
Location and description of site__________

Snow-condition (check one or more):
- Powdery or crumbly
- Packs with difficulty
- Packs easily
- Initially cohesive
- Drips when packed
- Drips without pressure

Other notes on snow-condition:__________

Data

Air-temperature__________ °C
Depth of snow, inches__________
Depth of sample from surface, inches__________
Calorimeter constant = K =__________ gr
Volume of warm water poured into calorimeter,__________ cc
W = Volume - (R × volume/100) W =__________ gr
W plus K =__________ gr

Temperature of snow, T = _____ °C, at depth of ____ inches
Volume of snow in tube, V = __________ cc
Initial temperature of warm water, I = __________ °C
Final temperature of mixture, F = __________ °C
I - F = __________ °C
Final volume of mixture__________ cc
M = Volume - (R × volume/100) M = __________ gr
Weight of warm water, W = __________ gr
Weight of snow, S = M - W = __________ gr
Density of snow = 100 × S/V = __________ %

R = % reduction in converting cc to gr

Temperature °C	R
0 - 35	0
35 - 57	1
57 - 75	2
75 - 90	3
90 - 100	4

Latent heat of ice or pure dry snow is 80 calories per gram
Quality of snow = q = grams of ice per gram of snow
1.00 - q = grams of water per gram of snow

Computations

Heat gained by snow requires raising temperature of ice-component to zero plus heat used in melting the ice plus raising temperature of melted snow from zero to the final temperature. The heat gained by the snow equals the heat lost by the warm water plus the heat lost by the calorimeter.

$(0.50 \times T \times S \times q)$ plus $(80 \times q \times S)$ plus $(F \times S) = (I - F)(W + K)$

With snow below 0°C, q is necessarily 100% and need not be measured.

With snow at 0°C, T = 0.0, therefore

$(80 \times q \times S) + (F \times S) = (I - F)(W + K)$

$(80 \times q \times S) = (I - F)(W + K) - (F \times S)$

Heat of melting = $H = 80 \times q = [(I - F)(W + K)/S] - F$

$(100 \times q)$ = __________ % quality

I - F = __________
W + K = __________
(I - F)(W + K) = __________
(I - F)(W + K)/S = __________
-F = __________
80 q = __________

Computed by__________ Checked by__________

Form 1

cal/gr, for melting pure ice has been given the designation of "quality" of snow, being analogous to the same term applied to steam used in engineering literature. Snow of 60 per cent ice and 40 per cent water has a 60 per cent quality and a heat of melting of 0.60 × 80 = 48 cal/gr.

Technique--The method used is to sample the snow-mantle as it is sampled for depth and density of snow. A wide-mouthed quart vacuum-bottle is used for a calorimeter. The snow-sample is added to a measured quantity of hot water of known temperature in the calorimeter. The final volume and final temperature of the mixture are observed. The difference between the initial and final volumes of water indicates the amount of snow in the sample. The temperature-difference indicates the amount of heat required to melt the snow.

Table 1--Measurements of heat of melting and of quality of snow made in New York State, March 3 and 4, 1941, in new-fallen snow except as noted

(Air-temperatures varied from 10° to 50° F during period of measurements)

Station	Initial snow-temp.	Initial temp. of warm water	Final temp. of mixture	Temperature-difference	Initial weight of warm water	Final weight of mixture	Diff. in weights = weight snow	Heat of melting snow	Quality of snow
	°C	°C	°C	°C	gr	gr	gr	cal/gr	per cent
Cranberry Lake	-1.0	52.2	27.8	24.4	302	381	79	75.5	94
		26.1	7.1	19.0	381	469	88	82.0	102
		48.1	17.2	30.9	292	395	103	81.0	101
		49.3	24.0	25.3	316	403	87	78.0	97
Wabeek, old		48.0	5.5	42.5	302	468	166	80.5	101
snow		49.0	5.0	44.0	317	495	178	81.8	102
Gale		49.0	22.0	27.0	284	370	86	78.0	97
		54.1	24.0	30.1	304	402	98	80.0	100
		63.0	13.5	49.5	213	348	135	77.0	96
		30.2	6.0	24.2	319	417	98	81.0	101
Big Tupper		47.0	9.1	37.9	304	442	138	84.1	105
		44.3	13.2	31.1	242	325	83	90.0	112
	-4.3	27.8	20.3	7.5	337	359	22	104.0	130
Little Tupper	-3.0	30.0	2.9	28.1	328	439	111	87.5	109
		44.9	9.5	35.4	282	404	122	82.0	102
		19.0	4.8	14.2	327	381	54	90.0	112
Long Lake	-1.0	26.2	1.3	24.9	298	395	97	83.8	105
		26.6	9.0	17.6	265	318	53	90.0	112
Raquette Lake	0.0	49.9	17.6	32.3	401	557	156	72.4	90
		35.3	3.7	31.6	247	365	118	71.5	89
		39.8	3.8	36.0	302	450	148	78.0	97
Inlet		39.8	4.1	35.7	264	402	138	73.0	91
		32.0	5.0	27.0	345	468	123	78.0	97
		40.5	6.5	34.0	289	427	138	73.1	91
Old Forge		37.6	21.2	16.4	246	287	41	91.0	114
		19.4	3.0	16.4	287	346	59	86.5	108

Table 1 shows the results of experimentation with varying sizes of snow-sample and with different initial water-temperatures. These and other data show that the experimental error is largely a function of the size of snow-sample. As the amount of melted snow is determined by taking the difference between initial and final volumes, this difference must be large for a reliable measurement. Best results are obtained by filling the calorimeter with approximately equal volumes of hot water and melted snow. Facility in estimating the amount of snow to be added comes with experience in making the quality determinations. An observed quality of more than 100 per cent indicates that the snow had an initial sub-freezing temperature.

Preliminary results--Observations of the quality of snow under a wide range of conditions have been made and are now being analyzed. Conclusions to date indicate that snow seems to have a minimum limiting value of quality, depending upon the volume and size of voids in the snow-structure. Coarse grainy snow may have a minimum quality of 70 per cent or 80 per cent. New snow, of finer particle size, has been observed to have qualities of less than 50 per cent in small shallow patches.

The calorimeter-constant can be obtained experimentally by the following method: The calorimeter is partly filled with a measured amount of hot water, and after the water and calorimeter come into equilibrium, the temperature of the water is observed. Next a measured quantity of cold water of known temperature is added. After equilibrium is reached the final temperature is observed.

The heat gained by the cold water equals the heat lost by the warm water plus the heat lost

Fig. 1

Fig. 2

by the calorimeter. Letting C = grams of cold water, W = grams of warm water, T_c = temperature of cold water in °C, T_w = temperature of warm water in °C, T_f = final temperature of mixture in °C, and K = water-equivalent of calorimeter, in grams

$$C\,(T_f - T_c) = (K + W)\,(T_w - T_f)$$

$$K = [C(T_f - T_c)/(T_w - T_f)] - W$$

In bringing the calorimeter to equilibrium, care should be taken to wet the entire interior surface. Uniformity in depth of immersion of the thermometer is a refinement in reducing the error resulting from differential expansion and from the heat lost or gained by the glass and mercury in the thermometer. The cork may be waterproofed by soaking it in high melting-point wax or by some other method. Volumetric observations of amounts of water have been found to be most practical under field-conditions. Volume in cc is converted to weight in grams as a simple temperature-function by Table 2.

Table 2--Values of R = per cent reduction in converting cubic centimeters to grams

Temperature	R
°C	Per cent
0	0
46	1
67	2
83	3
98	4

W = Volume - (R × Volume)/100

Field-kit--The field kit illustrated includes the following items (see Figs. 1 and 2): Carrying case; wide-mouthed quart vacuum-bottle with cork perforated for thermometer; 500-cc capacity glass graduate reading to one cc; snow-sampler tube with plunger; two laboratory thermometers, -10 to +110° C, reading to 0°.1 C; and portable alcohol burner for heating water with utensil.

The vacuum-bottle has a capacity of about 700 cc. Using equal volumes of hot water and melted snow, the observational precision is about one cc in 300 cc. The usual temperature-differences observed are about 30° C and reading to 0°.1 C, the precision is about 1 in 300, being of the proper magnitude relative to the volumetric measurements.

Observations of quality of snow made in Maryland and New York State early in 1941 have indicated a sufficiently wide variation in snow-quality to require its further study.

The Weather Bureau has definite plans to study snow-quality, not only as a means of determining the amount of heat to melt snow, but as a research tool in following movements of moisture through snow.

U. S. Weather Bureau,
Washington, D. C.

AN OUTLINE OF THE THERMODYNAMICS OF SNOW-MELT

W. T. Wilson

Introduction

Snow-melt determination, whether for estimates of seasonal volume, stream-flow forecasting, design of flood-control structures or other purposes, is fundamentally a matter of thermodynamics. The purpose of this paper is to discuss certain principles of thermodynamics that apply to the ripening and the melting of snow.

Temperature of the air seems to be the most significant single index of melting conditions. Snow-melt rates have frequently been expressed as functions of air-temperature measured in terms of degree-days above freezing.

However, to express snow-melt rates as a function of degree-days is to imply that other effects are either negligible, constant, or are simple temperature-functions. Among these effects are rate of air-transport, latent heat released by condensation of moisture on the cold snow-surface, and the net effect of incoming and outgoing radiation. An example of a negligible effect occurs in connection with radiation, when, with a heavy cloud-cover, the incoming and outgoing radiation may balance.

An example of a constant effect is the existence of fairly uniform wind-velocity during a given period over a certain basin. This results in turbulent exchange showing little variation except with variations in humidity and temperature.

The net effect of incoming and outgoing radiation is reflected in the air-temperature, and under certain conditions the radiation-effect may be expressed as a simple function of air-temperature.

It is possible at times, with very moist air, to express the heat gained by condensation on the snow-surface as a simple air-temperature function.

It seems appropriate, at the present state of development of snow-studies, to take inventory, and examine current knowledge in the light of a basic principle of hydrology; namely, that a satisfactory method or formula should stand between the extremes of over simplification on one hand and excessive refinement on the other hand. Over simplification results in the failure to recognize the effects of important variables. Excessive refinement may require data that are not available, and in their absence will invite too great a latitude of choice in applying judgment as a substitute for the data.

The outline given below will be followed:

(A) Theoretical melting at a point
- (1) Heat required to bring snow to the melting temperature
- (2) Rate of heat-transfer through the snow
- (3) Heat-diffusivity of snow
- (4) Sources of heat
- (5) Heat-losses
- (6) Temperature of the snow-surface

(B) Sources of moisture made available as the snow melts
- (1) Melting frost in the soil
- (2) Release of liquid water in the snow

(C) The effect of mechanical forces on the thermodynamics of snow-melt

(D) Areal significance of melting rates
- (1) Trajectory of air over snow
- (2) Effects of variation in elevation
- (3) Areal distribution of snow
- (4) Exposure of the snow

(E) Example

(A) Theoretical melting at a point

(1) <u>Heat required to bring snow to the melting temperature</u>--The examination of records of temperature-distribution in snow-mantles indicates that ordinarily, before snow-water makes its appearance, the entire snow-column is nearly isothermal [see 1 and others of "References" at end

of paper]. This seems to result from the normal seasonal march of temperature and from the circulation of heat, air, and moisture within the snow. An elementary computation shows that very little heat is required to raise the temperature of snow to its melting point, compared with the heat of fusion. For example, consider a pound of snow, with a specific heat of 0.50 BTU/lb/°F, and an initial temperature of 10° F above zero.

$Q = 0.50(32-10) = 11$ BTU, which is to be compared with the 144 BTU required to convert the pound of ice-crystals comprising the snow to liquid water. In metric units this is an initial temperature of -12° C and six calories to compare with the latent heat of fusion of 80 calories per gram.

(2) Rate of heat transfer through the snow--The conductivity of snow is a function of its density, age, and other properties, varying from about 0.0003 to 0.001 in cgs units. The greater conductivity is related to the greater density. For the present example, 0.0003 will be used because the less dense snow is ordinarily in the upper layers. These values of conductivity and other heat-transmission constants that will be used may be found and are discussed in the "Smithsonian physical tables." Assuming for the present a temperature-gradient through the snow of 1° C per cm, the heat-transfer will be

$$0.0003 \times (1/1) \times 3600 = 1.08 \text{ cal/cm}^2/\text{hr}$$

The temperature-gradient is a function of the specific heat of the snow, because some of the heat is used in heating the snow through which it passes.

(3) Heat-diffusivity of snow--To make use of both the conductivity and specific heat of the snow it is necessary to use Fourier's expression

$$Q = k\theta_0 \sqrt{t}/h\sqrt{\pi} = \text{heat-transfer in cal/cm}^2$$

during time t where k = conductivity = 0.0003 cal/cm^2/°C/cm/sec; θ_0 = °C, difference between the initial temperature of the snow-mass, and the temperature maintained at its surface; t = time in seconds; h = diffusivity = $\sqrt{k/c\rho}$; c = specific heat in cal/gr/°C; and ρ = density in gr/cc. Assume a deep snow-cover of initial temperature of 0° C, a cooling by the air that maintains the temperature at the snow-surface of -10° C, and that the snow has $K = 0.0003$, $c = 0.50$, and $\rho = 0.20$; h, then, is 0.055

$$Q = 0.0003 \times 10 \times \sqrt{t}/0.055 \times 1.77 = 0.031\sqrt{t}$$

or, expressing t in hours

$$Q = 1.86\sqrt{t}, \text{ cal/cm}^2 \text{ in t hours}$$

Table 1--Heat-diffusion through snow

Time, hours	Heat-transfer, cal/cm^2 through snow	
	Total	Per hour, during last hour
1	1.9	1.9
4	3.7	0.5
8	5.3	0.3
16	7.4	0.2
24	9.1	0.2
48	12.9	3.8 during second day
96	18.2	2.4 during fourth day

It is seen that the diffusion of heat through snow is very slow and that the temperature-gradient of 1° C/cm, assumed in the conductivity example can exist for only a short time.

Figure 1 shows temperature-profiles for the example given above.

The formula used in obtaining the temperature-profiles of Figure 1 is the standard Fourier formula for linear flow in a semi-infinite solid.

From the heat of fusion of ice of 80 cal/gr, and the factor of 2.54 cm per inch, a computation will show that 203 cal/cm^2 is required to melt an inch depth of water from dry snow at the melting temperature. Comparing the amount of heat involved in melting snow with the rate of heat-transfer through the snow, from Table 1 above, and the heat-capacity of snow, it appears that the rate of heat-transfer through the snow is very small. The rate at which snow can absorb heat at the surface, by virtue of its change of state, is limited only by the rate of heat-supply. On the contrary, snow can lose heat, only by transfer of heat to the surface by the very slow process of conduction through the snow itself.

From Table 1 and Figure 1 it appears that the lag between heating the snow and the melting

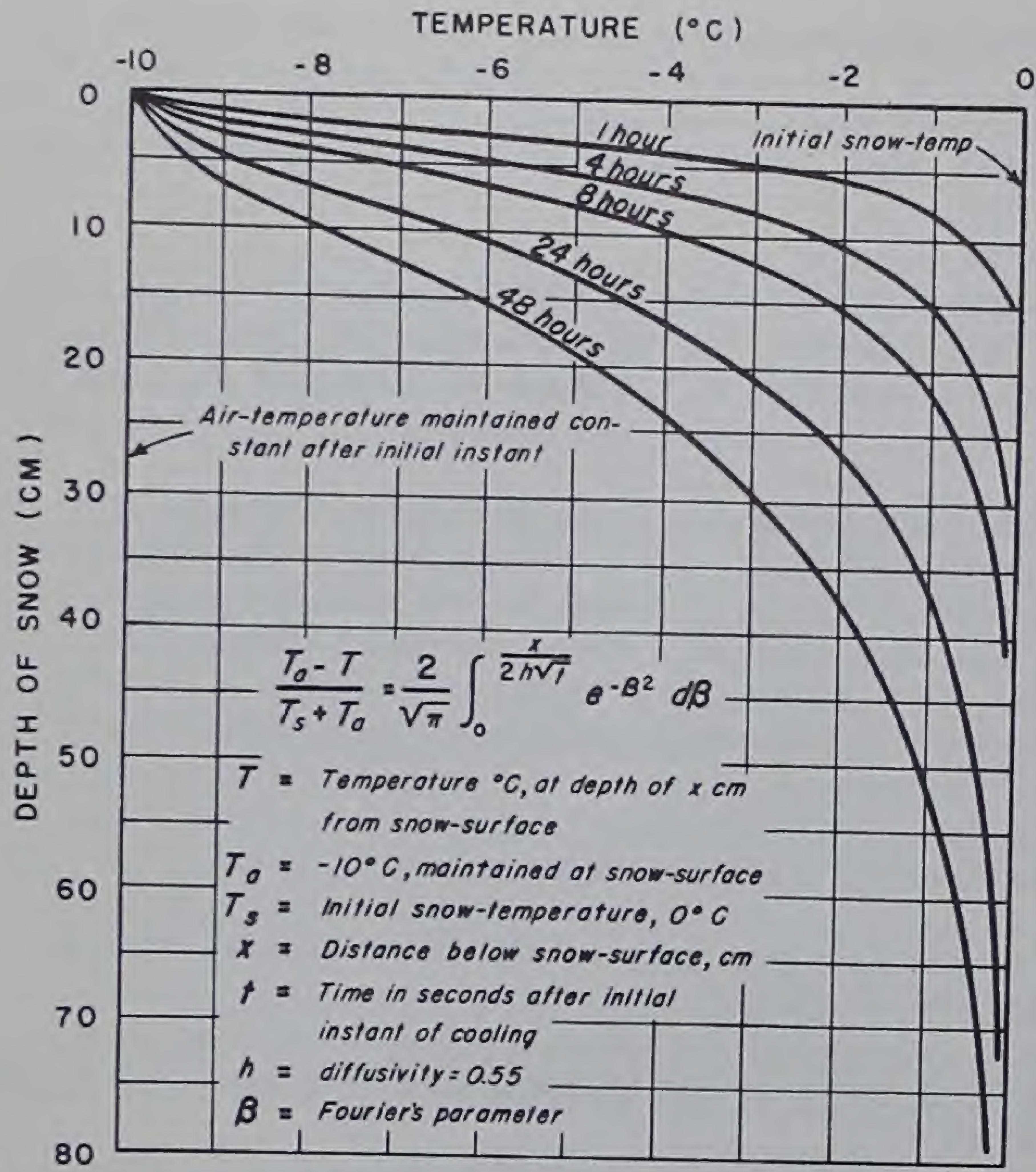

Fig. 1--Temperature-profiles through snow with initial snow-temperature of 0° C, with surface suddenly cooled to -10° C and maintained at -10° C continuously

of the snow is probably seldom more than ten calories per cm^2. This small quantity of heat is exceeded by errors in field-observations of heat-transfer or of snow-melt, and, in addition, its effect is obscured by the mechanical effects of water-movement in the snow. An example of this water-movement obscuring the thermodynamics occurs with intermittent thawing and freezing. As the snow melts and percolates downward there is temporary storage of melt-water by capillary detention. Cooling of the snow-surface freezes some of this water, forming the crust frequently observed. As a result, an unknown quantity of snow has melted, but not contributed to stream-flow, and may have to be melted several times. From the thickness of crust ordinarily observed, this quantity is believed to be small, and in cases of rapid or continuous melt may be ignored. It seems justifiable, therefore, in ordinary snow-melt computations, to ignore any heat-transfer not directly applied to melting the snow. Thus, snow may melt on the first warm day that occurs, regardless of the length and intensity of the previous cold season. A cold day, during a season of intermittent melting, need not be compensated for by a correspondingly warm day. If melting conditions exist during a small portion of a day, melt will occur, regardless of how cold the rest of the day is, or what the average temperature of the day may be. Experience confirms this. It can be assumed, for convenience, and with negligible error, that for ordinary snow-melt computations the entire snow-mantle is at 32° F.

(4) Sources of heat--The sources of heat are: (a) Conduction from air; (b) conduction from underlying soil; (c) warm rain; (d) radiation; (e) convection, turbulent exchange; (f) condensation, latent heat.

(a) Conduction from air--The conduction of heat through still air is even less than through snow, air having a k of 0.000055, c of 0.24, and h of 0.42, compared with snow having k = 0.0003, c = 0.50, and h = 0.055.

Effective heat-transfer by air can take place only by turbulent exchange and air-transport which will be discussed later.

(b) Conduction from underlying soil--Heat-transfer may take place from the soil to the snow or vice versa, depending upon the relative temperatures. Poor contact between the snow and soil, due to matted vegetation, may limit the heat-transfer to a minimum except when a layer of slush or water underlies the snow.

The heat-gain by the snow, from the soil, is limited by the rate of diffusion of heat through the soil, just as with snow. A light layer of snow may fall on warm soil and melt quickly, but a snow-cover of long duration is not only evidence, by its very existence, of the ineffectiveness of soil as a heat-source, but by the insulating effect of the snow, prevents the soil from becoming warm.

The thermal constants for soil vary, of course, with its moisture-content, but for average damp soil the factors may be taken as follows: k = 0.004; c = 0.45; and h = 0.073.

Assume soil with an initial uniform temperature of 10° C (50° F), and assume that the surface is maintained at 0° C by a cover of melting snow which absorbs heat as fast as the soil can transmit it.

$$Q = 0.004 \times 10 \times 60\sqrt{t}/0.073 \times 1.77, \text{ in calories per cm}^2 \text{ during t hours}$$

$$Q = 18.6\sqrt{t}, \text{ a diffusivity of ten times that of snow}$$

Table 2--Heat-diffusion through soil

Time, hours	Heat-transfer, cal/cm^2 through soil	
	Total	Per hour, during last hour
1	18.6	18.6
4	37.2	5.0
8	52.6	3.4
16	74.4	2.4
24	91.2	2.0
48	129	38 during second day
72	158	29 during third day
96	182	24 during fourth day

It is seen from Table 2 that the heat-transfer from the warm soil to the snow decreases as the duration of snow-cover continues. The temperature-profiles near the soil-surface are similar to those shown in Figure 1, for snow, the difference being the greater rate of diffusion through soil. After the thirtieth day of snow-cover the maximum rate is about 10 to 15 cal/cm^2/day. If the snow falls on frozen soil, or if the soil freezes through a light snow-cover, this rate will be greatly reduced.

In view of the magnitude of other heat-sources and the uncertanties involved, it would be an unjustifiable refinement to include warm soil as an important snow-melt heat-source during the spring season. The discharge of many snow-covered basins studied amounts to about a hundredth of an inch per day during the winter season. The winter discharge would be far greater than it is if the soil melted much snow.

Occasionally, the soil-surface may be heated by solar radiation penetrating a thin snow-layer. Opinion differs on the magnitude of this effect, but it is generally ignored.

Significant snow-melt takes place only at the surface exposed to the air. The appearance of water at the soil-surface results, not from appreciable melting by the soil, but from percolation downward through the snow.

(c) Melting by warm rain--Warm rain carries heat to the snow, and the amount of melt resulting can be computed by the following formula

$$D = P\ (T - 32)/144$$

where D is inches of depth of water melted from the snow, P is inches of depth of rain, the heat of fusion of ice is 144 BTU per pound, and T is temperature of rain in °F, of which the wet-bulb observation is considered a fair measure. The wet-bulb temperature is a regular Weather Bureau observation. If a thermometer-bulb were placed in a falling rain-drop, its exposure would not be greatly different from that of the wet-bulb thermometer with its wick. Figure 2 illustrates a graphical solution of this formula.

The energy of impact of falling rain may be shown, by considering the mechanical equivalent of heat, to be a negligible heat-source.

(d) Melting by radiation--Transfer of heat to or from the snow-surface by radiation depends upon the net effect of incoming and outgoing radiation. The incoming radiation depends largely upon time of year, latitude, degree of cloudiness, and the albedo or reflecting power of the snow. Snow-crystals reflect light so effectively that the penetration beyond the first few crystal-layers is very small, and the reflection can be assumed to take place at the snow-surface. The albedo varies from 60 to 90 per cent, depending upon the character of the snow-surface [8,9]. Sun-cups [10] represent a high-altitude phenomenon of trapped insolation, and in most watersheds may be ignored.

Because of the small number of pyrheliometers in the country, direct observations of solar radiation are not available for most basins. As an expediency, the radiation-income may be expressed as a function of cloud-cover or per cent of sunshine [4,9,12].

Figure 3 has been prepared, indicating the magnitude of radiation heat-gain by the snow. Inasmuch as the atmospheric moisture intercepts only about 12 per cent of the insolation, it is believed acceptable to use the average value of radiation received at the Earth's surface. The Sun's angle of incidence relative to the varying aspects of the snow-surface in a basin is important, but adequate data are rarely available. Various degrees of forest-cover obviously affect the rate of heat-transfer by radiation. The elevation, time of occurrence, and density of the cloud-cover are recognized deficiencies in the data.

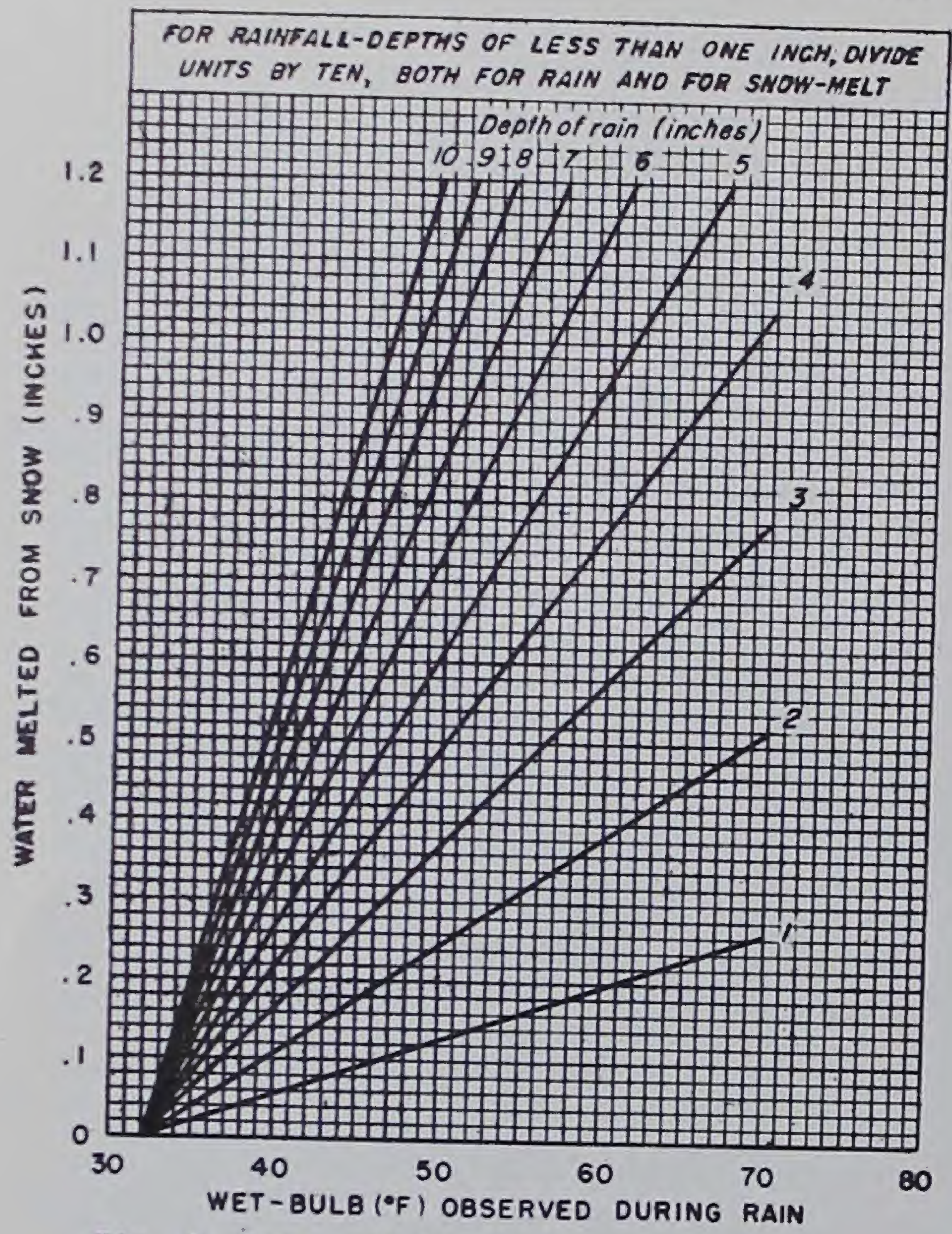

Fig. 2--Snow-melt from warm rainfall with snow-surface at 32° F

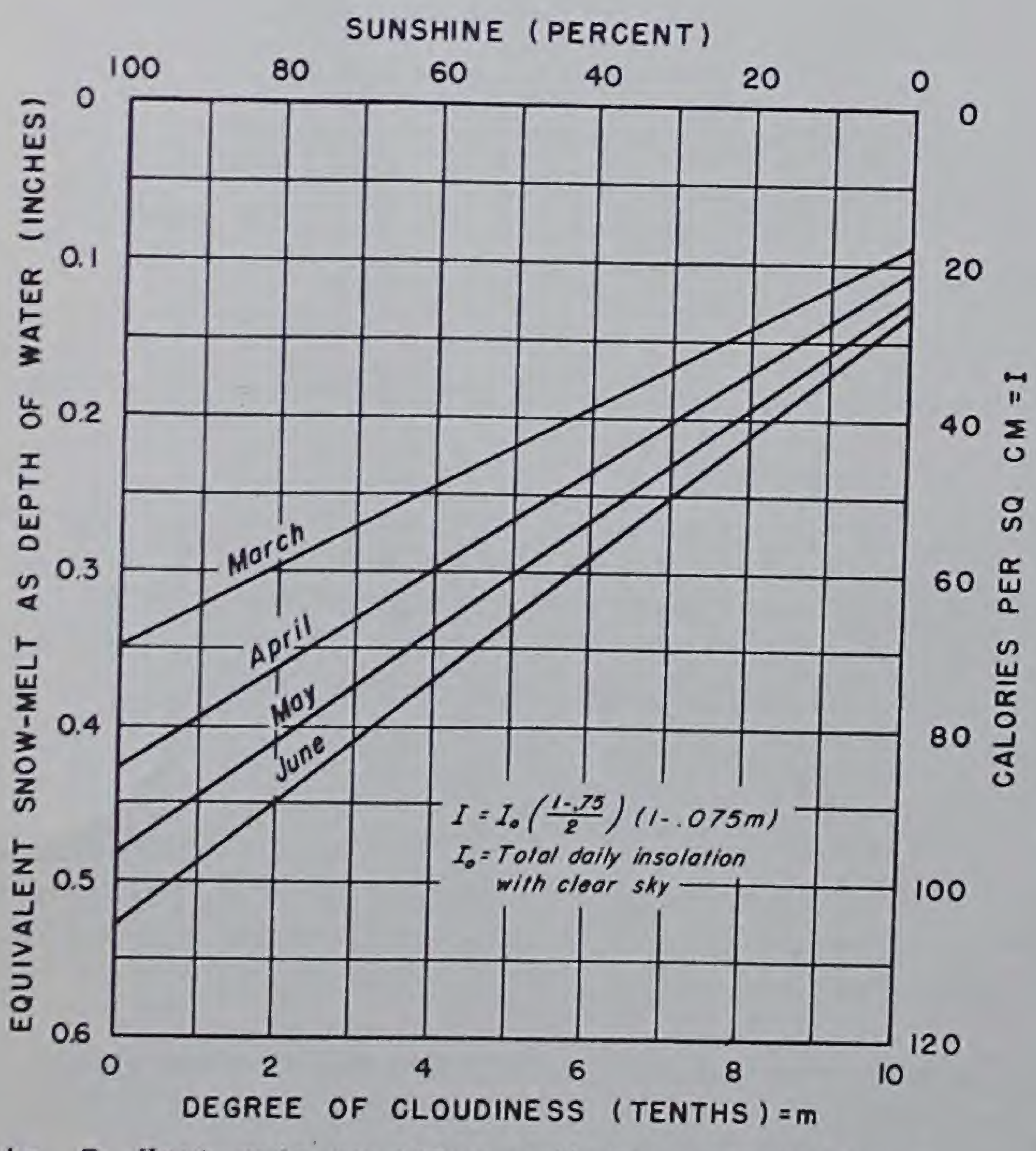

Fig. 3--Heat-gain by solar radiation per half-day period beginning or ending at noon (Latitude 40° to 48° north, albedo 75 per cent, direct plus diffuse radiation on horizontal surface)

The altitude of the snow-surface is a minor refinement. Other refinements can be listed, but until satisfactory evaluation of the albedo of the snow under various conditions is possible, as a field-observation, other factors need be only approximated.

Assuming a reasonable value of radiation-income of 600 cal/cm^2/day late in March with a latitude of 40° north, and no clouds: The snow-cover will reflect about 450 cal and absorb the remaining 150 cal/cm^2/day.

(e) Turbulent exchange of heat--The turbulent exchange, or convection, of heat at a snow-surface can be expressed as a linear function of wind-velocity and air-temperature under certain conditions [7, 8, 9, and 13]. Among these conditions are consistency in exposure of instruments as to elevation above the ground and roughness of the ground. The air near the snow, being colder and heavier than the air immediately above it, tends to produce stable stratification, and with a light wind, the turbulent exchange may not be a linear function of the wind-velocity. This is a subject of current study in the Weather Bureau. The wind-velocity is less near the ground than at higher elevations, making the anemometer height an important factor. As to roughness, the wind-structure over a smooth snowfield will differ from that of a metropolitan anemometer-exposure or a dense forest-canopy. The temperature of the air immediately above a melting snow-surface is only a little higher than 32°, increasing with elevation to a maximum several feet above the ground. Above this maximum the temperature decreases with elevation throughout the turbulent layer. The rate of heat-exchange from a melting snow-surface may be expressed as follows

$$D = KV (T - 32°)$$

where D is depth of water melted from snow in six hours, V is wind-velocity in mph, T is dry-bulb temperature °F, and K is a constant involving the latent heat of ice, exposures of instruments, air-density, conversion of units, and certain considerations involved in the theory of turbulence. This subject is discussed in detail in Mr. Light's paper "Analysis of high rates of snow-melting" in this Part of the Transactions of 1941 of the American Geophysical Union. Figure 4 shows the rate of snow-melt by turbulent exchange of heat with a K of 0.001, a value indicated by preliminary analysis of three experimental basins established

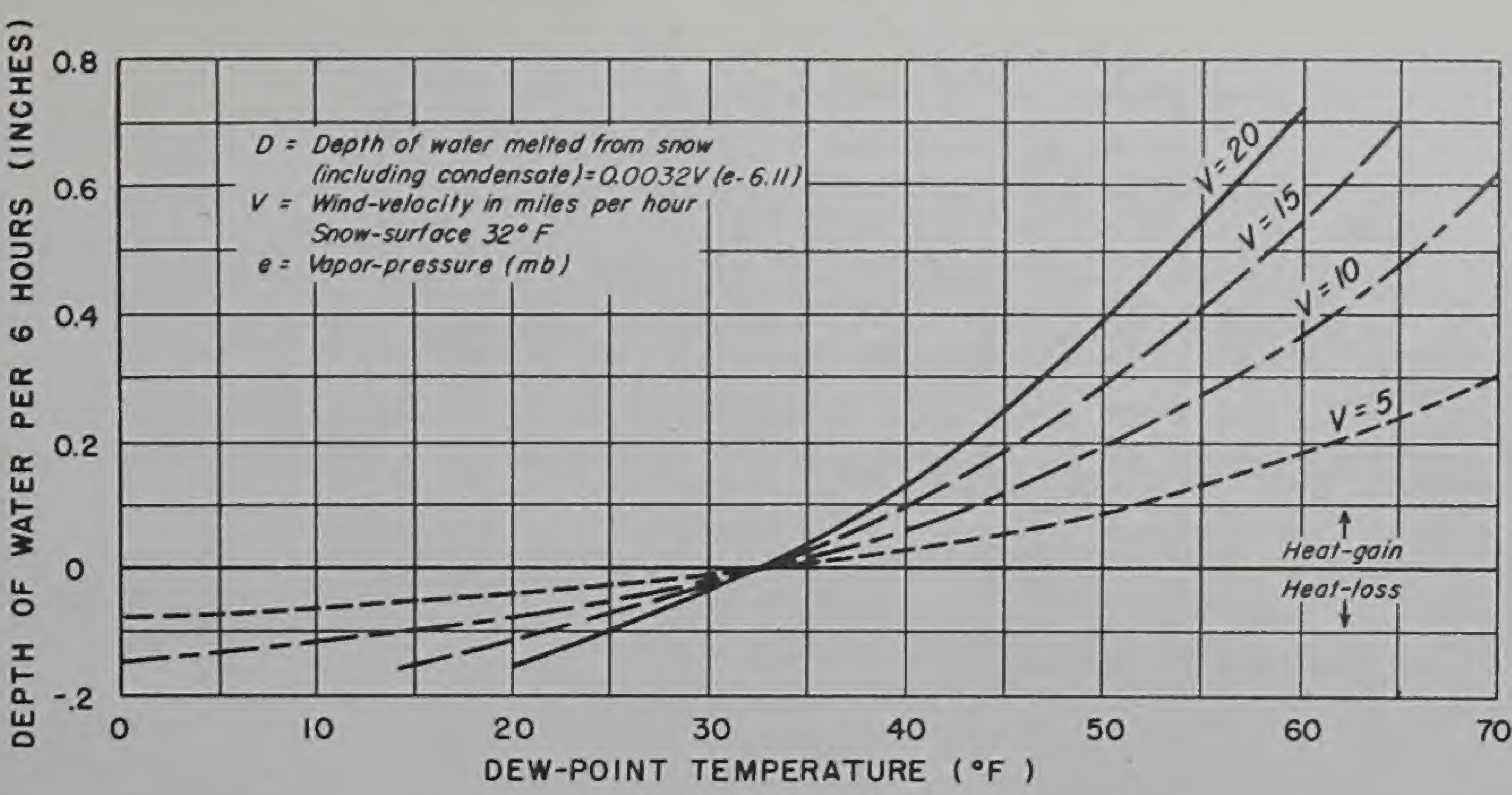

Fig. 4--Snow-melt by heat-transfer from air by turbulent exchange

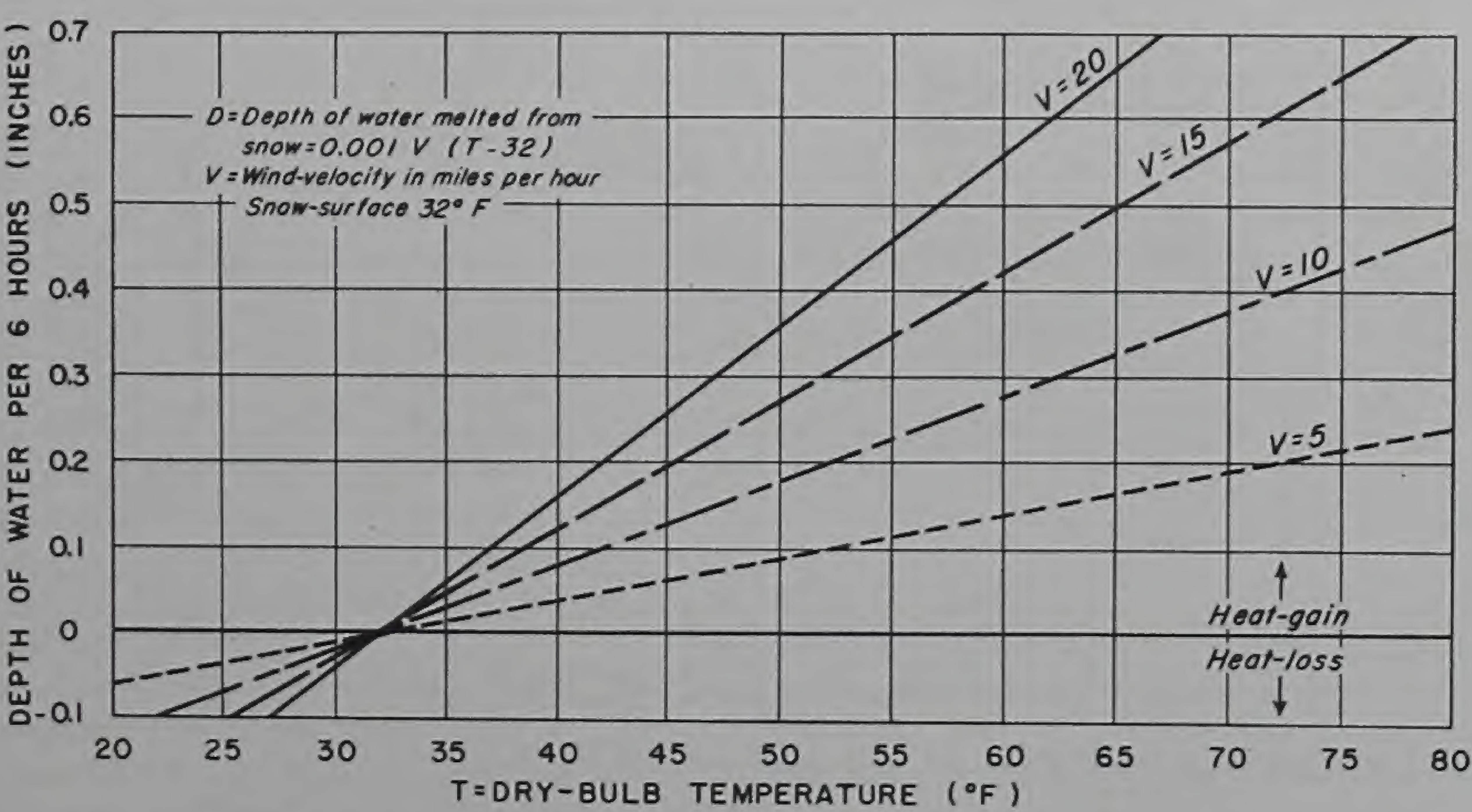

Fig. 5--Snow-melt by latent heat of condensation of moisture on snow-surface by turbulent exchange

and studied by the Weather Bureau in Yellowstone Park, Wyoming [11]. These basins have been examined by the method described briefly under the heading "Example" appearing at the end of this outline.

(f) Heat of condensation--Warm moist air transfers heat to the snow by liberation of the latent heat of vaporization of the moisture deposited on the cold snow-surface. The moisture, as vapor, is carried to the snow-surface by turbulent exchange in a manner analogous to transfer of heat

$$D = K_1 V\ (e - 6.11)$$

where D is depth of water melted from snow in six hours plus condensate added to the snow, V is wind-velocity in mph, e is vapor-pressure in millibars, and K_1 is a constant involving the latent heat of ice, exposure of instruments, conversion of units, and bears a definite relation to K. This subject is discussed in Mr. Light's paper, referred to above. If e is measured at the same height above the ground as T, K_1 is approximately 3.2 times K, for basins of elevation from 0 to 3,000 feet, and for units of measurements used. Advantage of this fact is taken in determining, by empirical methods, the values of K and K_1. Figure 5 shows the rate of snow-melt by condensation, using dew-point observations as a measure of e. The value 6.11 in the formula is the vapor-pressure at the surface of the melting snow. If the dew-point is less than 32° F, the vapor-pressure of the air will be less than 6.11, and evaporation instead of condensation will occur, thus cooling instead of heating the snow. The general formula for convection plus condensation may be written

$$D = KV\ [(T - 32) + 3.2\ (e - 6.11)]$$

Records have demonstrated, and examples will show, that ordinarily heat-transfer by convection and condensation far exceeds that by any other means. From Figures 4 and 5 saturated air at 50° F and ten mph will melt, in six hours, about 0.2 inch of water from snow by convection, and an equivalent amount by condensation, depending upon exposure of instruments and other considerations. The constant in the turbulent-exchange formula, given above, seems to be a basin-characteristic, and evidence indicates that it is fairly conservative for basins having similar characteristics. It appears that these characteristics may be identified and evaluated only by empirical methods.

(5) Heat-losses--Heat-losses are: (a) Heat-transfer to air; (b) conduction to soil; (c) outgoing radiation; and (d) evaporation.

(a) Heat-transfer to air--When the air is cooler than the snow-surface there will be heat-transfer from the snow to the air by convection. This heat-loss, in a manner similar to heat-gain, may be computed by the formula

$$Q = K\ V\ (T_s - T_a)$$

where Q is rate of heat-exchange, T_s is the snow-surface temperature, and T_a is the air-temperature at some distance above the snow.

The rate of loss of heat by conduction up through the snow has been shown to be very small. Figure 1 and Table 1 illustrate how, with a sharp temperature-inversion in the upper snow-layer, the snow-surface temperature can change rapidly, and over a wide range, with only a few calories of heat-transfer. With the air-temperature less than the snow-temperature, the dew-point will necessarily be less than the snow-temperature, and no condensation can occur. Therefore, the only other means by which the snow-surface can be supplied with heat to lose to the air is by radiation. Sverdrup [8] and others have shown that the albedo of frozen snow is higher than for melting snow, and values of 80 to 90 per cent may ordinarily exist. Paradoxically as it may seem, the outgoing radiation may more than compensate for the net radiation-income with a cold dry snow-surface on a clear sunny day. It is seen that the rate of heat-loss to the air is always very small.

(b) Conduction to soil--The heat-loss from snow to the underlying soil is limited by the rate of diffusion through snow, except for the heat carried downward by percolating water. The heat carried by percolating water may be seen from the discussion of snow-melt by rain to be negligible, in view of the temperature and quantity of the percolating water involved. Therefore, the rate of heat-loss from the snow to the soil is very small.

(c) Outgoing radiation--Outgoing radiation is not to be confused with the reflection of incoming radiation. Snow radiates as a black body by the Stefan-Boltzmann law, $R = k\ T^4$, but selective absorption and back radiation by atmospheric water-vapor and clouds complicate the study of radiation-influences. Snow being both a good reflector and a good radiator may appear to violate Kirchoff's law, that "a good emitter is a good absorber." However, Kirchoff's law applies to a given wave-length, and snow reflects short-wave radiation while it emits long-wave radiation. In the absence of upper-air soundings, the water-vapor content of the air must be estimated from surface-observations, and from assumptions of reasonable values of humidity aloft.

The outgoing radiation from a snow-surface at 32° F amounts to a heat-loss of about 0.45 cal/cm^2/minute. This outgoing radiation is reduced a varying amount, determined largely by the quantity and temperature of moisture in the air. Assuming clear sky with unusually dry air, the reduction may be only 50 per cent, the net outgoing radiation amounting, then, to about 160 cal/cm^2 in 12 hours. The heat-loss at night may be quite great, limited by the rate of transfer of heat to the snow-surface, and the resulting snow-surface temperature.

The absorbing effect of atmospheric moisture is great on the long-wave outgoing radiation, in contrast to its relatively small effect on the incoming radiation. From examination of a number of published articles [3, 4, 5, 6, and 9], Figure 6 has been prepared, showing the amount of outgoing radiation from melting snow in terms of data available for most basins. The diagram of Figure 6 indicating average outgoing radiation in the absence of upper-air soundings is naturally susceptible to error in cases where surface-observations and inferences from surface-data are inadequate. The variations in temperatures aloft, and cloud-heights, are sometimes very important. However, the two factors most important in determining the variation in net outgoing radiation from a melting snow-surface are shown in Figure 6, namely, the amount of moisture in the air, and degree of cloud-cover. Meteorological analysis of synoptic maps and soundings at neighboring stations may be of assistance where night-cloud observations are

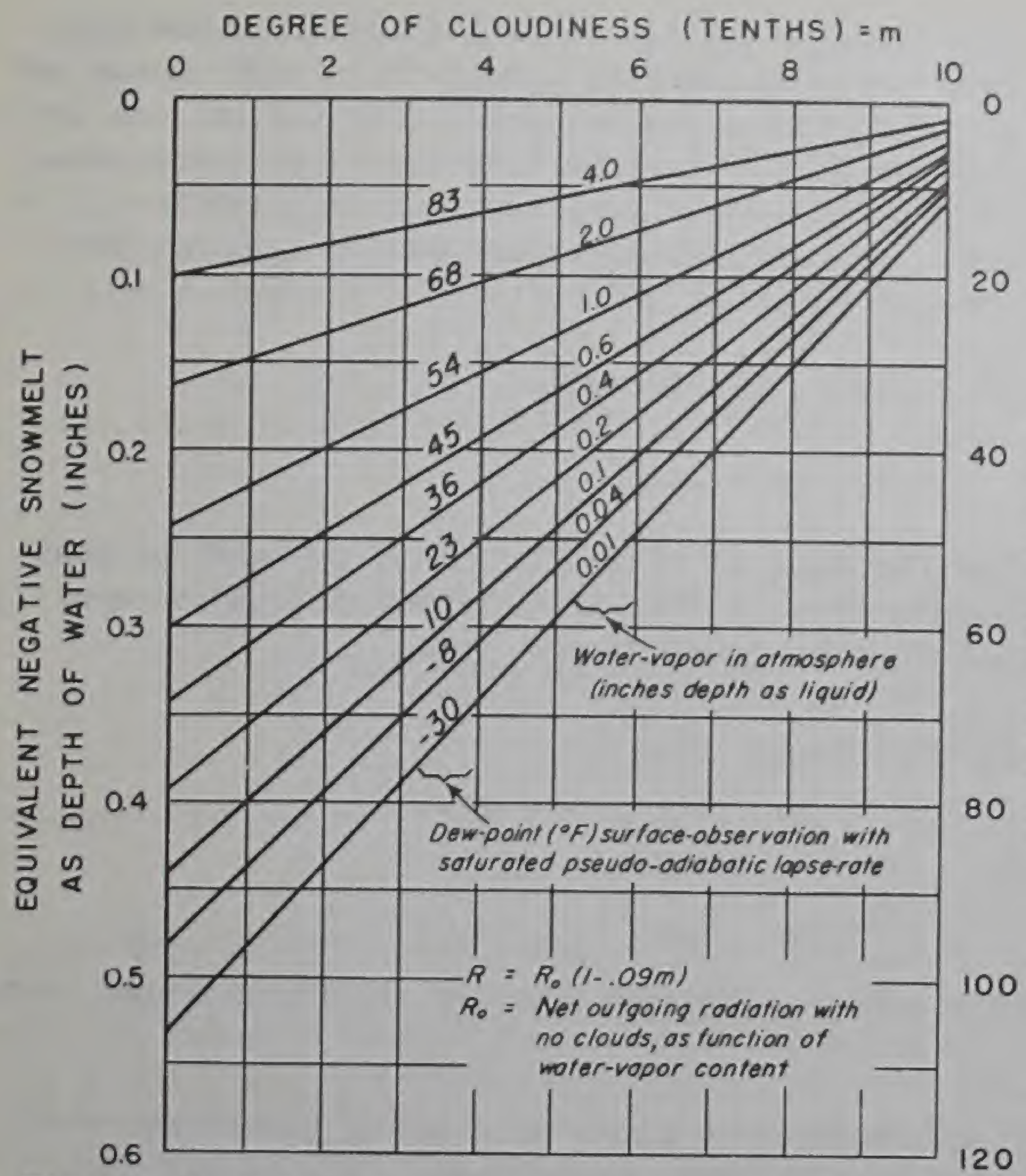

Fig. 6--Heat-loss by outgoing radiation per six-hour period from snow-surface at 32° F (Effect of water-vapor obtained from Elsasser chart with simplifying assumptions)

lacking. The dew-points shown on Figure 6 may be used as follows: A dew-point of 54° F at the surface, with saturated pseudo-adiabatic lapse-rate, indicates a water-vapor content of 1.0 inch measured as depth of liquid water. An assumption of humidity of 50 per cent throughout the atmosphere would reduce this inch to half an inch. Estimates of quantity of water-vapor in the atmosphere from surface-observations require special meteorological knowledge.

(d) Evaporation--Evaporation can take place only when there is a supply of the necessary heat of vaporization. As has been shown, the rate of heat-transfer from storage in the snow is small. The only other sources of heat are radiation and turbulent exchange from the air. If the dew-point of the air is less than 32° F and more heat than is necessary for evaporation is supplied, there will be melting simultaneous with the evaporation. The "heat-loss" part of Figure 5 represents evaporation, and may be used in this connection. If the dew-point of the air is less than 32° F and the heat-supply is deficient for the evaporation-opportunity, the snow-surface temperature will decrease, and melting will not occur. At night, for evaporation to occur, the heat-gain by convection must supply the heat lost by outgoing radiation in addition to supplying the heat of vaporization.

(6) Temperature of the snow-surface--The temperature of the snow-surface is determined by the direction and magnitude of heat-transfer at the snow-surface. With a continuous heat-gain, the snow will melt, and the temperature will be 32° F. From the nature of the agents transferring heat to or from the snow, there is a tendency for equilibrium between the snow and its environment. The colder snow becomes, the greater is its rate of heat-gain and the smaller its rate of heat-loss. A decrease in the snow-surface temperature decreases the evaporation-opportunity, decreases the outgoing radiation, and increases the tendency toward heat-gain by condensation and turbulent exchange. The temperature of the snow-surface is not only determined by air-temperature, but is an important factor in determining the air-temperature. The snow-surface temperature will be analyzed under the following heads: (a) Turbulent exchange of heat; (b) evaporation and condensation; and (c) radiation.

(a) Turbulent exchange of heat--At the snow-surface the snow-temperature and the air-temperature must be identical, no discontinuity of the vertical temperature-profile being possible.

With heat-transfer from the snow to the air the temperature lapse-rate in the air must exceed the dry adiabatic lapse-rate. The dry adiabatic lapse-rate represents equilibrium between the air-temperature at various elevations and the gain or loss of heat due to changes of pressure in the vertical movement of the air. Therefore, within the turbulent layer of the air receiving heat from the snow, the air in the upper layers is potentially colder than air in the lower layers. Because of the fact that cool air is heavier than warmer air, there is a limit to the temperature-gradient, beyond which the air would be subject to violent overturning. This is known as mechanical instability, and is represented by an extreme lapse-rate of 1° F in about 50 feet. With the usual thermometer height of 20 feet or less, the air-temperature is seldom as much as a degree less than the snow-surface temperature. Except for a radiation or evaporation-inversion, therefore, and when the snow is not melting, the air-temperature can be taken as the temperature of the snow-surface. In reference to Figure 4 it may be observed that the "heat-loss" part of the diagram will seldom be used to the extent indicated. That is, with a melting snow-surface in contact with the air, a thermometer of ordinary exposure could not show a temperature much below 32° F.

(b) Evaporation and condensation--In the preceding paragraph, it was shown that the air-temperature near the snow cannot be much less than the snow-surface temperature, but it can be greater. An example of its being greater may be described as an evaporation-inversion, in which the snow-surface is cooled by evaporation. The greatest evaporation-inversion will occur when all the heat required for evaporation is supplied by the air. There can be no discontinuity in the saturation vapor-pressure at the snow-surface. The saturation vapor-pressure, e, at the snow-surface is a function of the snow-surface temperature.

In the discussion of condensation appearing earlier, the formula

$$D = KV\ [(T - 32) + 3.2\ (e - 6.11)]$$

appears. This formula can be used for the present purpose by relating inches of melt to heat-transfer; by deducting the condensate, which changes the 3.2 coefficient to 2.8; and by equating the heat required for evaporation to the heat supplied by convection. Thus

$$(T_{air} - T_{snow}) = 2.8\ (e_{snow} - e_{air})$$

from which

$$T_{snow} = [T_{air} - 2.8\ (e_{snow} - e_{air})]$$

in which the air-properties are measured in a thermometer-shelter, and the snow-properties exist at the snow-surface.

The physical process of making a wet-bulb observation by means of a sling-psychrometer is closely related to the problem of determining the snow-surface temperature. The temperature of the wet-bulb represents equilibrium between heat-gain from the air and heat-loss by evaporation. The saturation-pressure over a snow-surface is only a fraction of a millibar less than over water (or in ordinary air) at the same temperature. This, with other differences, is sufficiently small to permit use of the wet-bulb observation as a measure of the snow-surface temperature. This is true, of course, only when the snow-surface temperature results from equilibrium in the turbulent exchange of moisture and heat. This condition is satisfied with snow which is not melting, and which is experiencing a balance of incoming and outgoing radiation. In this case, the snow-surface temperature is within a degree or two of the wet-bulb temperature of the air and the wet-bulb depression is a measure of the evaporation-inversion.

(c) Radiation--With snow that is not melting, the difference between the wet-bulb temperature of the air and the snow-surface temperature is an index to the radiation-gain or loss. Where the snow-surface temperature is between -20° F and 32° F the net outgoing radiation with a clear sky may be estimated at about 20 to 50 calories per square inch per 6-hour period [3, 5, and 6].

An interesting phenomenon is the greenhouse-effect of ice-windows. This is frequently seen on the southern side of drifts, where a cavity or pit in the snow is covered with a sheet of ice about as thick as a window-pane, and sometimes as large. The ice melts or sublimes very slowly, sometimes lasting for days, being nearly in equilibrium or even cooled by the outside air. However, the thin ice-pane is penetrated by incoming radiation, and the snow, subject to this greenhouse-effect, melts very rapidly. In the dry air of alpine regions these sun-cups or sun-pits, occur without the ice-windows.

(B) Sources of moisture made available as the snow melts

In addition to the actual melting of snow, water other than that comprising the snow is sometimes released, during the melting process.

(1) <u>Melting frost in the soil</u>--Autumn soil-priming, followed by a hard freeze and the subsequent spring thaw, produces a stream-flow contribution related to the snow-melt problem. While the rates of this source of inflow for short periods of time are relatively low, the effect for a season, or in analyzing the hydrograph of a basin, has frequently been found to be quite significant.

(2) <u>Release of liquid water in the snow</u>--Due to antecedent rain or to initial melting at the snow-surface, a snow-column may contain considerable liquid water. This stored water will be released by no expenditure of heat other than that which is required to melt the ice-crystal matrix of the snow-structure.

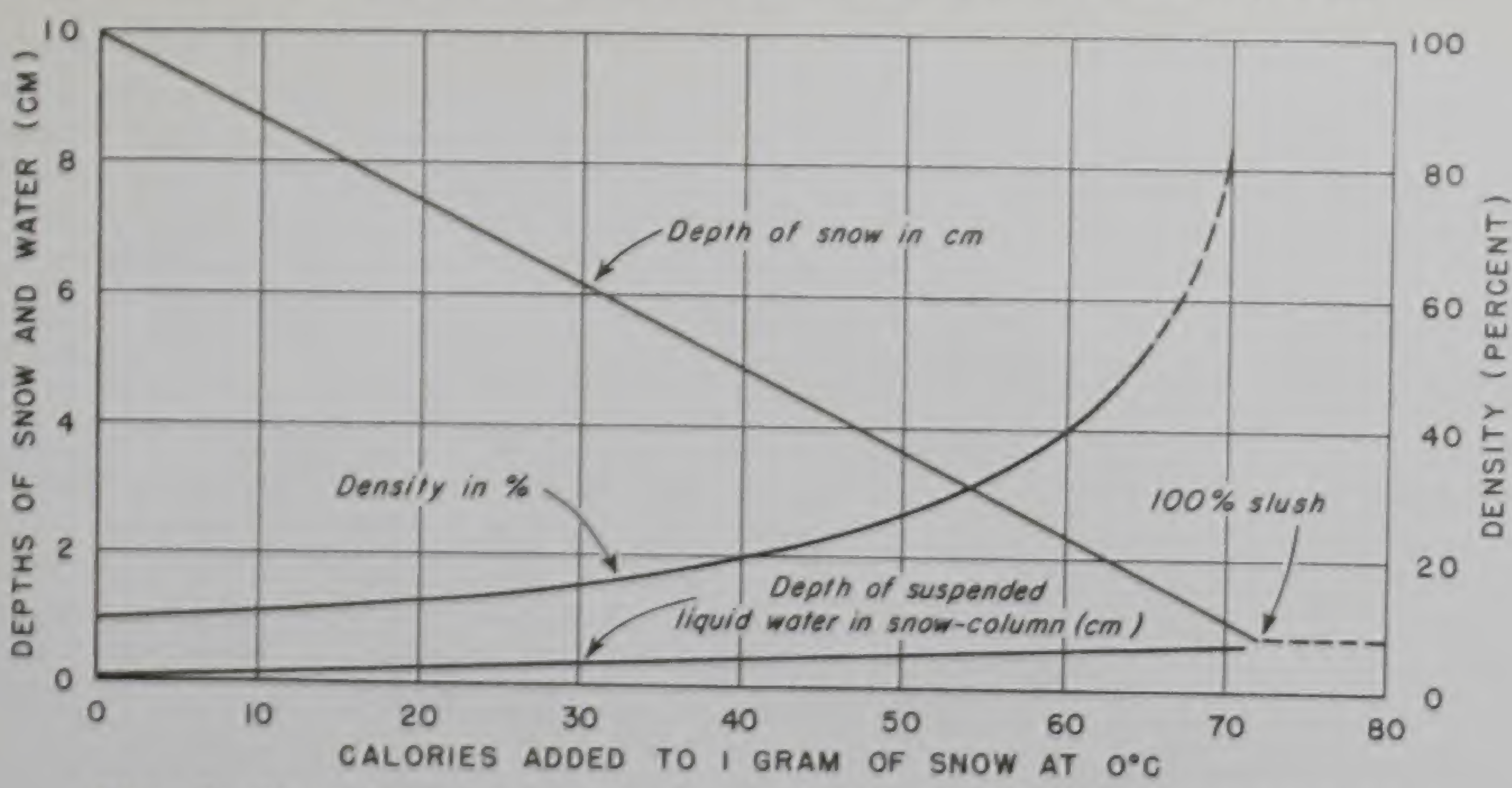

Fig. 7--Ripening of 10-cm column of snow with original density of 10 per cent and 0° C initial temperature

Thus the heat of melting of snow in calories per gram of snow may be less than the latent heat of fusion of 80 calories per gram of ice. Figure 7 shows the effect of melting at the upper surface of a hypothetical column of one gram of snow, originally ten cm high assuming no drainage from the column. The changes in snow-depth, density, and depth of suspended liquid water in the snow-column as heat is applied, are to be noted. As the snow melts, the water percolates downward and builds up a capillary head which may be likened to a perched water-table at the ground-surface. Discharge of the suspended water does not occur until the capillary head is more than balanced by gravity. This may result from an increase in head; or from an increase of pore-size by change in snow-structure caused by erosion, melting, or some other influence. An increase of head may result from the contribution of rainfall and, with saturated snow, the resulting runoff may greatly exceed either the amount of rainfall or the amount of snow melted by the rain.

Figure 7 shows that to convert snow, which due to antecedent melting has a density of 20 per cent, entirely to water, requires only 40 calories per gram. This is only 50 per cent of the heat of fusion of ice. This value of 50 per cent is the ratio of heat of melting of snow in calories per gram of snow to the latent heat of fusion of ice, which is 80 calories per gram of ice. This ratio may be designated as the quality of the snow. The term "quality" has a good precedent by analogy to the same term which is the standard engineering expression for the dryness or purity of steam. The change of state from water to ice is analogous to the change of state from water to steam. Snow with a quality of 100 per cent is pure dry snow. Snow with a quality of 50 per cent is half ice and half water.

The 100 per cent slush-point of Figure 7 is only a theoretical limit, and would be, physically, a mixture of water with a small amount of ice floating or distributed in it. Such a mixture would be essentially fluid in consistency and appearance, and could not be assumed to remain on a basin as a condition antecedent to runoff.

The quality of a snow-mantle is a measure of the amount of heat required for melting, and the study of possible lower limits of snow-quality is a current Weather Bureau project.

(C) The effect of mechanical forces on the thermodynamics of snow-melt

The density of snow may increase not only by melting, but also by compression from its own weight or by changes in shape of the snow-crystals. Alternate evaporation and condensation will increase the density of the snow, and the total net heat-transfer may be zero. Usually snow on the ground increases in density from a combination of causes. The melting of an upper layer not only removes this layer, but percolation of the melt-water into the lower layers and refreezing by contact with the cold snow changes the snow-texture from a feathery to a coarse condition. If the increased density of pure dry snow results from a process involving no gain or loss of heat, the full 80 calories per gram will be required for melting.

The relation of melting to runoff involves not only the questions of infiltration, frozen and thawing soil, and subsurface flow, but also the consideration of factors causing a lag or lead in the time between the melting causes, and the appearance of water at a stream's edge.

Factors tending to lag the runoff from melting snow are (1) storage in the snow and (2) percolation-rates through the snow-structure. Among factors tending to cause a lead in runoff relative to melt are (1) slides or mass-flow, (2) erosion and transportation of snow by rain or other runoff-water, and (3) the mechanical and wetting effect of rain. This wetting effect consists of overloading the snow with liquid water beyond its capillary capacity.

The foregoing discussion indicates that the mechanical effects occurring during ripening and melting of snow obscure the thermodynamic processes.

However, studies have shown that on an areal, instead of a point-basis, lack of uniformity of condition and depth of snow frequently "dampen out" what otherwise might be wide variations between melting processes and observed melting rates. In some cases it appears that ripening and other changes in the snow-condition are conservative functions of basin-characteristics or of the melting season. The ripening of the snow may occur immediately prior to the melting, instead of during a long period, this lag being obscured by the areal effect of the melting zone. Nevertheless, numerous exceptions to methods now in use indicate that our observations of snow-condition are inadequate.

Measurements of water-equivalent and density do not indicate with sufficient reliability the readiness with which snow will melt. The Weather Bureau has recently developed a practical calorimeter-technique for quantitative determination of snow-quality in the field.

(D) Areal significance of melting rates

(1) Trajectory of air over snow--As an air-mass passes over a snow-field, losing heat to the snow, the air experiences a corresponding amount of cooling. The result is a reduction of the temperature of the air, and a decrease in the rate of heat-transfer. This effect may be illustrated by the following example.

Assume a mean air-temperature of 10° C (50° F) during the process, and a velocity of transport of ten meters per second. The velocity of air-transport ordinarily exceeds the surface-observations of wind-velocity. Assume a reasonable value of 700 meters for the thickness of the turbulent layer. Take 0.0012 for the air-density, 0.24 for the specific heat, and assume that this air-mass loses ten calories per cm^2 in one hour by turbulent exchange of heat (which can be determined by a diagram similar to Figure 4). The average temperature-reduction of this air may then be computed to be

$$T = 10 \text{ cal}/0.24 \times 0.0012 \times 700 \times 100 = 0\overset{\circ}{.}5 \text{ C}$$

or about 1° F per 25 miles of horizontal air-travel over melting snow. Similarly, as moisture is condensed on the cold snow-surface, the air is dried, and the rate of melting by condensation decreases.

Attempts to observe the rate of cooling of an air-mass with a trajectory over snow have met with too little success to confirm or disprove the theory, or to establish satisfactory empirical relationships at this time.

(2) Effect of variation in elevation--The effect of variation in elevation may be considered under the following heads: (a) Air-temperature, (b) humidity, and (c) wind-velocity.

(a) Air-temperature--The cooling of air as it rises, in passing from the lower to the higher portions of a basin, is well known, as is the converse effect of a chinook. Inasmuch as the rate of change of temperature with change of elevation is 5°5 F per 1,000 feet, except when accompanied by condensation or evaporation, this is a most important consideration in watersheds of rugged topography.

(b) Humidity--The vapor-pressure is fairly conservative with respect to changes in elevation, unless evaporation or condensation occurs. The dew-point, as a measure of vapor-pressure, may be corrected for changes in elevation, the change in dew-point being 1° F per 1,000 feet, decreasing with elevation as the atmospheric pressure does.

(c) Wind-velocity--It is well known that a valley-anemometer does not measure wind-velocity on an adjoining mountain. Under certain conditions, however, the valley-anemometer may be a good index to average wind over a small basin, the index-relation being a basin-characteristic. However, at times, the higher elevations of a basin may be exposed to meteorological conditions

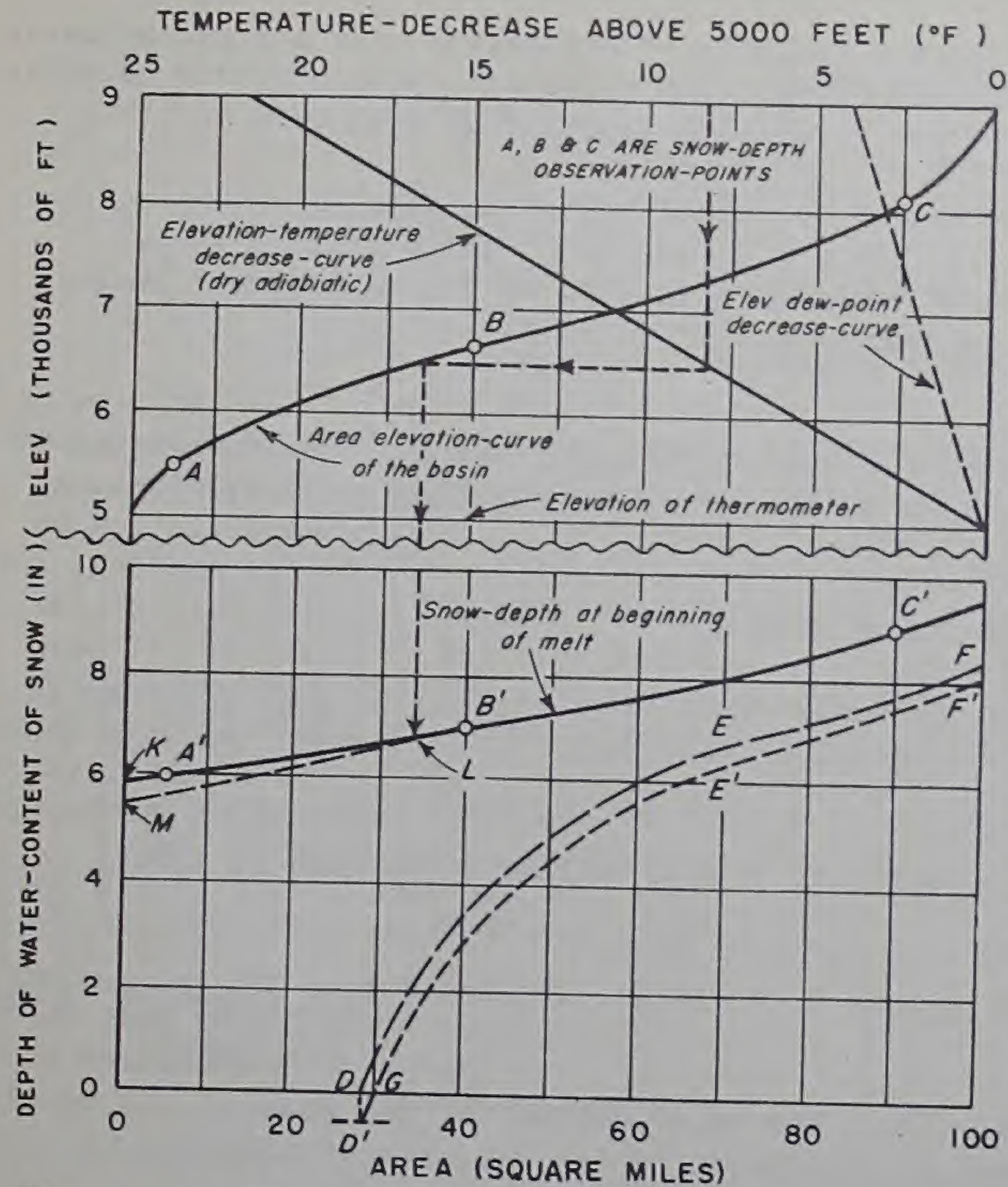

Fig. 8--Graphical determination of effects of area and elevation on snow-melt

in no way related to those of the lower elevations. This may refer not only to wind-velocity, but to wind-direction, humidity, and temperature.

(3) Areal distribution of snow--Almost without exception the snow-cover on any basin is non-uniform, both as to quantity and condition of the snow. As a result, the shallow snow disappears while the deeper snow is still melting, and a decreasing portion of the basin-area contributes runoff. In a typical mountain basin, a melting band progresses up slope during the melting season, having varying width at various times and places depending upon exposure or aspect, initial snow-depth and condition, nature of forest or other cover, and a variety of other factors.

(4) Exposure of the snow--Every basin presents varying aspects as to the angle of the Sun, differences in vegetative cover, and other variable influences that must be considered in giving areal significance to melting rates. These variations seem to balance out or combine to form a basin-characteristic such as variations in the areal distribution of percolation-rate, detention-storage, and even rainfall seem to do in applying the unit-graph principle.

(E) Example

Figure 8 illustrates a method by means of which the rate and progress of snow-melt can be computed. Subject to occasional check against snow-observations and stream-flow during the melting period, this method shows definite possibilities as a forecasting tool.

Let it be assumed in Figure 8 that snow-observations at A, B, and C define a snow-depth versus elevation curve A'B'C'. Assume further, for convenience, that the basin-area is small enough to require no correction for cooling of the air as a result of its trajectory over snow, and that the meteorological station at elevation 5,000 feet is so situated that observations made there can be considered applicable to the basin--as to wind-direction, for example.

Assume, as the melting season approaches, that a 6-hour period occurs during which the dry-bulb temperature is 40°, dew-point 32°, wind-velocity 20 mph, no rain, and equilibrium between radiation income and outgo. From the elevation versus temperature-decrease curve, and the area-elevation curve, 32° dry bulb occurs at elevation 6,500 feet, corresponding to 34 square miles of area. Zero-melt occurs at this point, L. From Figure 4, the melt at elevation 5,000 feet and 40° is 0.16 inch, which is indicated on the curve at point M. A working graph, instead of the example shown in Figure 8 has an expanded snow-depth scale, permitting the plotting of 0.16 inch with precision. The area of triangle KLM is the amount of snow-melt, being (0.16/2) (34/100) = approximately 0.03 inch average depth from the entire basin.

Assume for the following 6-hour period, that the mean temperature is 35°, with a dew-point of 28°, other conditions remaining the same as before:

The effect of convection will be seen, from Figure 4, to be about 0.06 inch. From Figure 5, the effect of condensation will be negative, amounting to 0.06 inch. The net effect is zero-melt. The quantity of snow lost by evaporation or sublimation is about one-eighth of the 0.06 inch, the one-eighth being approximately the ratio of latent heat of fusion of ice (or dry snow) to the latent heat of vaporization or of sublimation.

As the dry-bulb and dew-point lines in Figure 8 decrease with elevation, they may meet at what is known as the condensation-level. Above this level, the lapse-rate is about 3° F per 1,000 feet, the dew-point and dry-bulb temperatures decreasing together at this rate.

As the season progresses, assume that successive increment layers of varying thickness and width have disappeared, until the profile DEF in Figure 8 is reached. Assume that a 6-hour period with average dry bulb of 70°, dew-point of 50°, wind-velocity of ten mph, and no rain or radiation occurs. In a manner corresponding to that described in the first part of this example, the new profile (GE'F') is obtained.

The effect of radiation, both gain and loss, is reduced by forest-cover. The net effect of radiation at various elevations will be influenced by the local melting conditions resulting from other causes.

Conclusions and summary

(1) The amount of heat required to raise the temperature of a quantity of pure dry snow to the melting point is very small compared to the amount of heat required to convert the same snow entirely to water.

(2) Ripe snow consists of a matrix of ice-crystals with a varying proportion of liquid water held in suspension.

(3) The heat of melting of snow may vary within wide limits, depending upon the proportion of liquid water in the snow.

(4) Important heat-transfer takes place only at the upper surface of the snow.
(a) The rate of heat-gain by the snow is determined by the net rate of heat-supply.
(b) The net rate of heat-loss from the snow is limited by the low rate of heat-conduction through the snow.

(5) Relative magnitude of heat-transfer by various means is indicated in the following tabulation:

(a) Heat-gain

Means of heat-gain	Extreme conditions	Approx. cal/cm^2/day
Air convection, turbulent exchange	70° dry bulb, 20-mph wind	600
Condensation, heat of vaporization	60° dew-point, 20-mph wind	600
Net radiation gain	Very moist air, cloudy at night	200
Warm rain	4" at 50° wet-bulb temperature	100
Underlying soil	New snow	20

(b) Heat-loss

Means of heat-loss	Extreme conditions	Approx. cal/cm^2/day
Outgoing radiation	Very dry air and clear sky	200
Evaporation, heat of vaporization	10° dew-point, 45° dry-bulb, 20-mph wind, high convection heat-gain	150
Convection, turbulent exchange	Air colder than snow-surface, high insolation-gain	20
Underlying soil	Frozen soil	20

A rate of heat-loss from the snow exceeding 5 to 20 calories per cm^2 per day can take place only by a concurrent supply of heat to the snow-surface from outside the snow.

Acknowledgment--The writer wishes to express his appreciation to Merrill Bernard and Phillip Light for helpful criticisms and suggestions.

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ANALYSIS OF HIGH RATES OF SNOW-MELTING

Phillip Light

Introduction

The Hydrometeorological Section of the Weather Bureau has been engaged in a study directed towards a determination of maximum possible snow-melt rates over selected drainage-basins. Since snow-melting is a thermodynamic process the investigation pertained largely to a consideration of the various factors influencing the transmission of heat to the snow-mantle. Of these factors, it was found that for high melting rates the heat contributed by convection and condensation of moisture through turbulent diffusion of warm moist air are the important heat-sources. The problem is, then, largely a consideration of the upper limit values of air-temperature, humidity, and wind-velocity compatible with an adequate snow-cover, and the relationship of these values to the rate of snow-melt.

To meet the problem of predicting the melt resulting from a given meteorological situation, a theoretical melting formula has been developed utilizing modern theories of atmospheric turbulence. In order to apply this formula to actual drainage-basins it was necessary to develop a procedure for determining areal melting rates, taking into account overall changes in the air-mass, produced by melting snow and by surface-characteristics of the basin. It is to be understood that this paper deals only with actual snow-melt, that is, the inflow of melt-water to the snow-cover, and not with the subsequent disposition of the melt-water.

Effective snow-melt

Warm moist air flowing over a snow-field transfers heat to the snow in two ways. First, there is the direct heat-exchange due to the difference in temperature between the air and snow. Secondly, moisture is brought down to the snow-surface and condensed, releasing latent heat of condensation amounting to 600 calories per cc of water deposited. Since the heat of fusion of ice is 80 calories per cc, the moisture condensed on the snow-surface melts 7.5 times its own weight of snow.

Defining the effective snow-melt as combined melt and condensate, there follows the simple relationship

$$D = (Q + 600\ F)/80 + F = (Q + 680\ F)/80 \qquad (1)$$

where D is the effective snow-melt in centimeters per second, Q is the heat-transfer by convection in calories per cm^2 per second, and F is the water-transfer in centimeters per second.

The above equation can be generalized to include the case of reverse moisture-transfer or evaporation from snow to warm dry air. Figure 1 shows the temperature and vapor-pressure distribution of the layer of air directly above the snow for the two cases of condensation and evaporation with a melting snow-surface. During melting, the snow-surface temperature remains constant at 32° F. A thin film of air in contact with the snow is saturated with moisture and in equilibrium with the snow-surface. This requires a vapor-tension of the snow-surface equal to the saturated vapor-pressure of air at 32° F, 6.11 millibars. Above this air-film the temperature increases with height in both cases but the vapor-pressure increases with height for condensation and decreases with height for evaporation. Evaporation signifies a loss of both heat and moisture from the snow-cover and is indicated by a negative value of F in equation (1).

Theory of heat- and water-transport

In a solid body, heat flows from regions of high temperature to regions of low temperature through the process of molecular conduction. The quantity of heat transported through a unit cross-section is proportional to the product of the molecular heat-conductivity of the material and the temperature-gradient normal to the section. While molecular conduction of heat also occurs in the atmosphere it may be considered negligible in this discussion, the important mechanism of heat-conduction in the atmosphere being eddy-diffusion. Analogous to molecular diffusion, heat-transport across a horizontal section of turbulent air results from vertical motion of eddies and is proportional to the product of the coefficient of turbulent exchange and the vertical temperature-gradient. Likewise, since vertical movements of air-particles are also responsible for diffusion of moisture from one layer to another, the rate of moisture-transport is determined by the product of the vertical moisture-gradient and the coefficient of turbulent exchange.

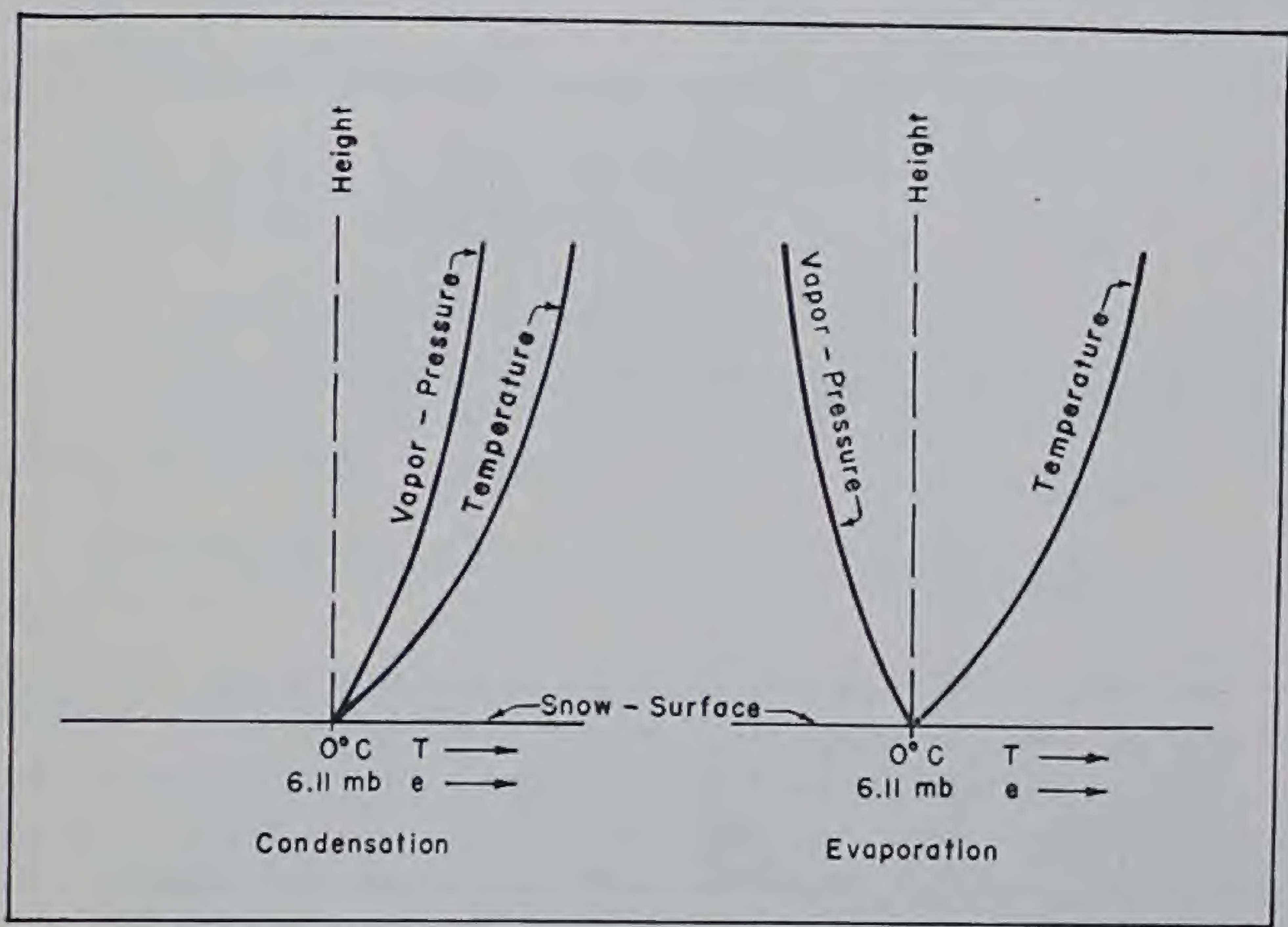

Fig. 1

The coefficient of turbulent exchange, or eddy-conductivity, depends on three factors: Wind-velocity; surface-roughness; and the stability of the layer of air next to the snow. Since it is clear that an increase of wind-velocity or roughness is accompanied by an increase in the degree of turbulence, it follows that at a fixed level there must be a corresponding increase in eddy-conductivity. In the literature of atmospheric turbulence, the term of roughness-parameter has been adopted to designate the degree of surface-roughness and is proportional to the average height of roughness-elements of the surface. It may be obtained in the following manner: Wind-observations at several elevations above a given surface are plotted against height, the curve is extrapolated to zero wind-velocity, and the height-intercept denotes the roughness-parameter of the surface. The average roughness-parameter of a level snow-field, determined by Sverdrup [see 1 of "References" at end of paper] as a result of numerous experiments, is 0.25 cm.

Since vertical air-motions in the atmosphere take place adiabatically, continued action of turbulence within a given air-mass will eventually produce an adiabatic lapse-rate of temperature in that air-mass. Conversely, any action which decreases the lapse-rate, such as downward heat-transport, stabilizes the air-mass and inhibits turbulence. Therefore, a cold surface tends to produce stability in a warm air-mass flowing over it and thus acts to dampen turbulence. Rossby [2] has shown that for an adiabatic atmosphere, or, in other words, air in which no stabilizing influences are present, eddy-conductivity varies directly with wind-velocity and height, which necessitates a logarithmic distribution of wind-velocity with height. Neglecting the effect of stability and assuming that the processes of momentum transfer and heat- and moisture-transfer are the same, temperature and vapor-pressure will also follow the logarithmic law.

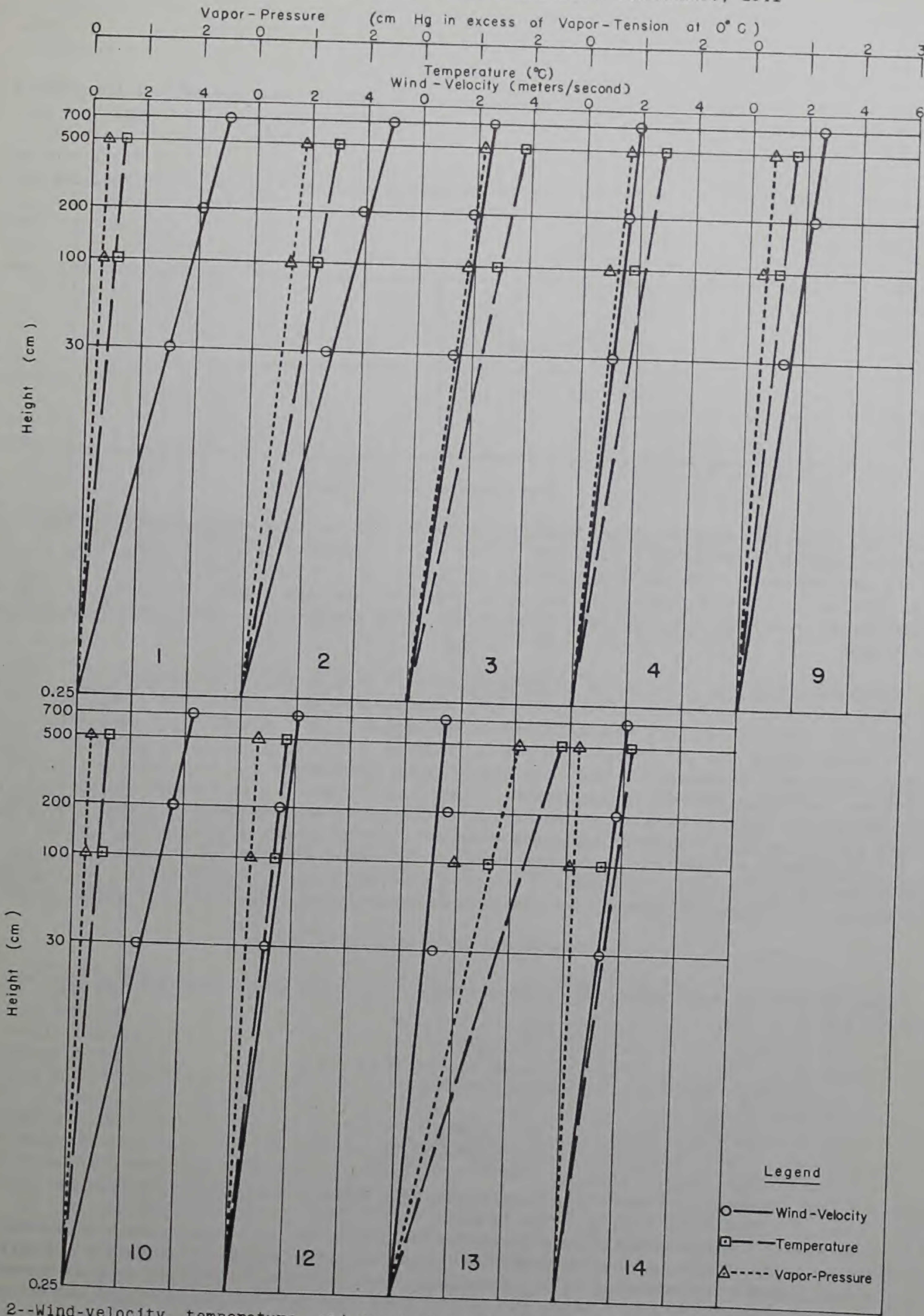

Fig. 2--Wind-velocity, temperature, and vapor-pressure distribution above a melting snow-surface

Theory and observations both indicate that strong winds counteract the effect of stability and that with increase of velocity the vertical distribution of meteorological elements near the ground approaches the logarithmic law. This may be seen in Figure 2, showing graphs of average wind-velocity, temperature, and vapor-pressure at several elevations during various periods of melting from observations made by Sverdrup over a level snow-field. Height is plotted on a

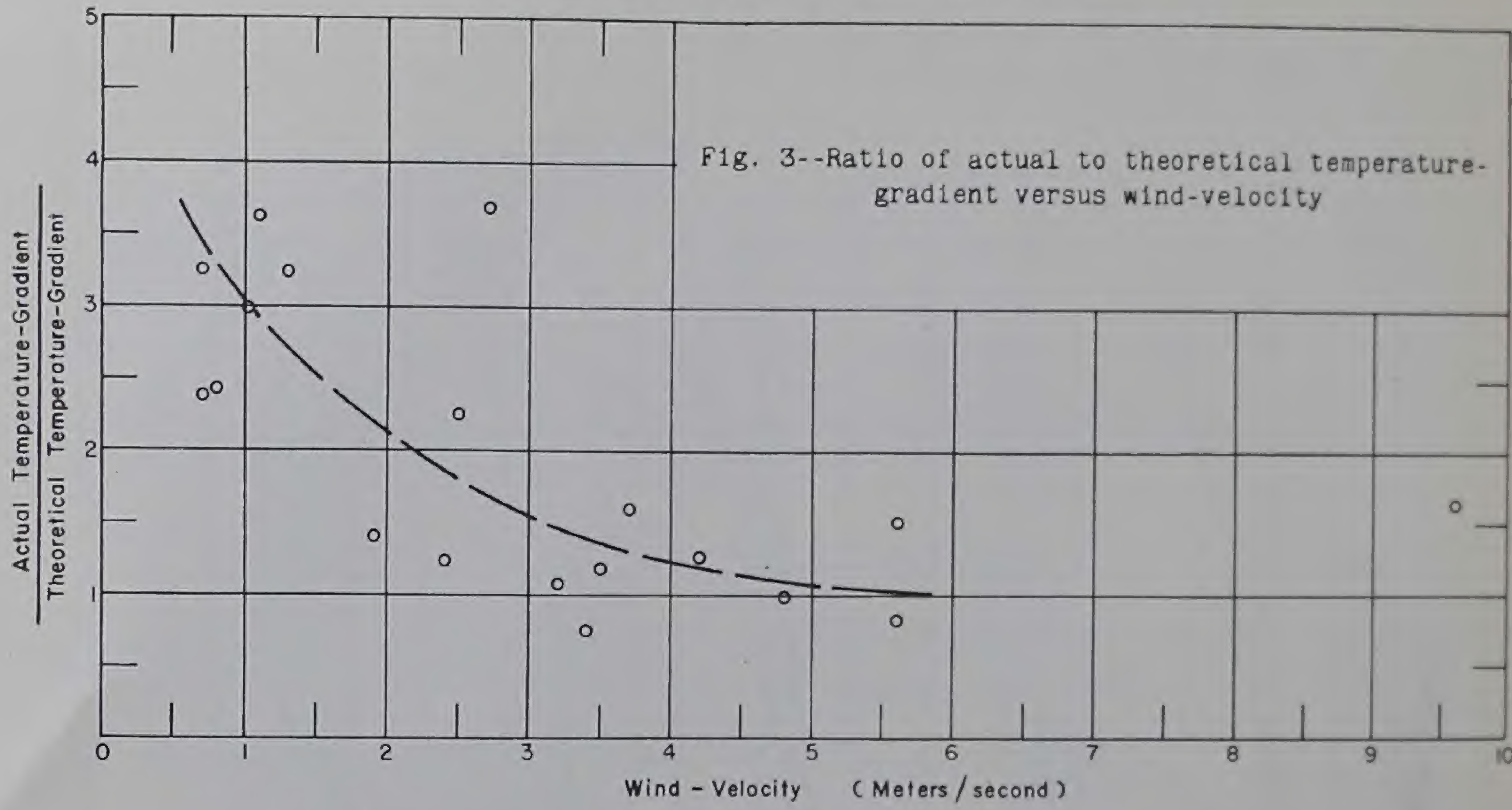

Fig. 3--Ratio of actual to theoretical temperature-gradient versus wind-velocity

logarithmic scale and wind-velocity, temperature above freezing, and vapor-pressure in excess of saturated vapor-pressure at 0° C along the linear scale. Straight lines have been drawn connecting the zero-values at 0.25 cm, the roughness-parameter, to the upper observations. If we examine periods 1, 2, and 10, which are marked by comparatively high winds, it can be seen that observations at intermediate levels fall close to the lines representing logarithmic distributions with height.

Further evidence is afforded by an investigation of data presented by Angstrom [3]. Here, air-temperatures at two levels and wind-velocity observations at a single level, together with snow-surface temperatures, are available for non-melting periods. Measurements were made in the arctic region during the polar night and cooling through outgoing radiation is partly balanced by heat-transport from the air so that the snow-surface temperature remains fairly stationary during the individual periods of observation. This made it possible to compute temperature-gradients on the basis of an assumed logarithmic distribution of temperature between the snow-surface and the upper thermometer and compare these values to actual gradients represented by the air-temperature differences at the two levels. The ratios between the two gradients are plotted against wind-velocity in Figure 3 and show a definite trend towards unity with increase of velocity, confirming the theory of a logarithmic distribution with height for strong winds.

Theoretical melting formula

The formulae for heat- and water-transport according to the logarithmic law, in the form given by Sverdrup, are

$$Q = \frac{c_p \rho k_o^2}{\ln(a/z_o)\ln(b/z_o)} U (T - T_o) \tag{2}$$

$$F = 0.622/p \frac{\rho k_o^2}{\ln(a/z_o)\ln(b/z_o)} U (e - e_o) \tag{3}$$

where Q = heat-exchange, F = water-vapor exchange, c_p = specific heat of air at constant pressure = 0.24, ρ = density of air, k_o = von Karman's coefficient = 0.38, U = wind-velocity at anemometer-level, T = air-temperature at hygrothermograph-level, T_o = snow-surface temperature, e = vapor-pressure of air, e_o = vapor-tension of snow-surface in mb, p = atmospheric pressure in mb, a = elevation of anemometer in mb at hygrothermograph-level, b = elevation of hygrothermograph, z_o = roughness-parameter = 0.25, and ln = natural log. All values are expressed in cgs units.

For a melting snow-surface, T_o = 0 and e = 6.11 millibars. Substituting these values together with Q and F given by equations (2) and (3) in equation (1) we obtain for the rate of effective snow-melt

$$D = \frac{\rho k_o^2}{80 \ln(a/z_o)\ln(b/z_o)} U [c_p T + (e - 6.11) 423/p] \tag{4}$$

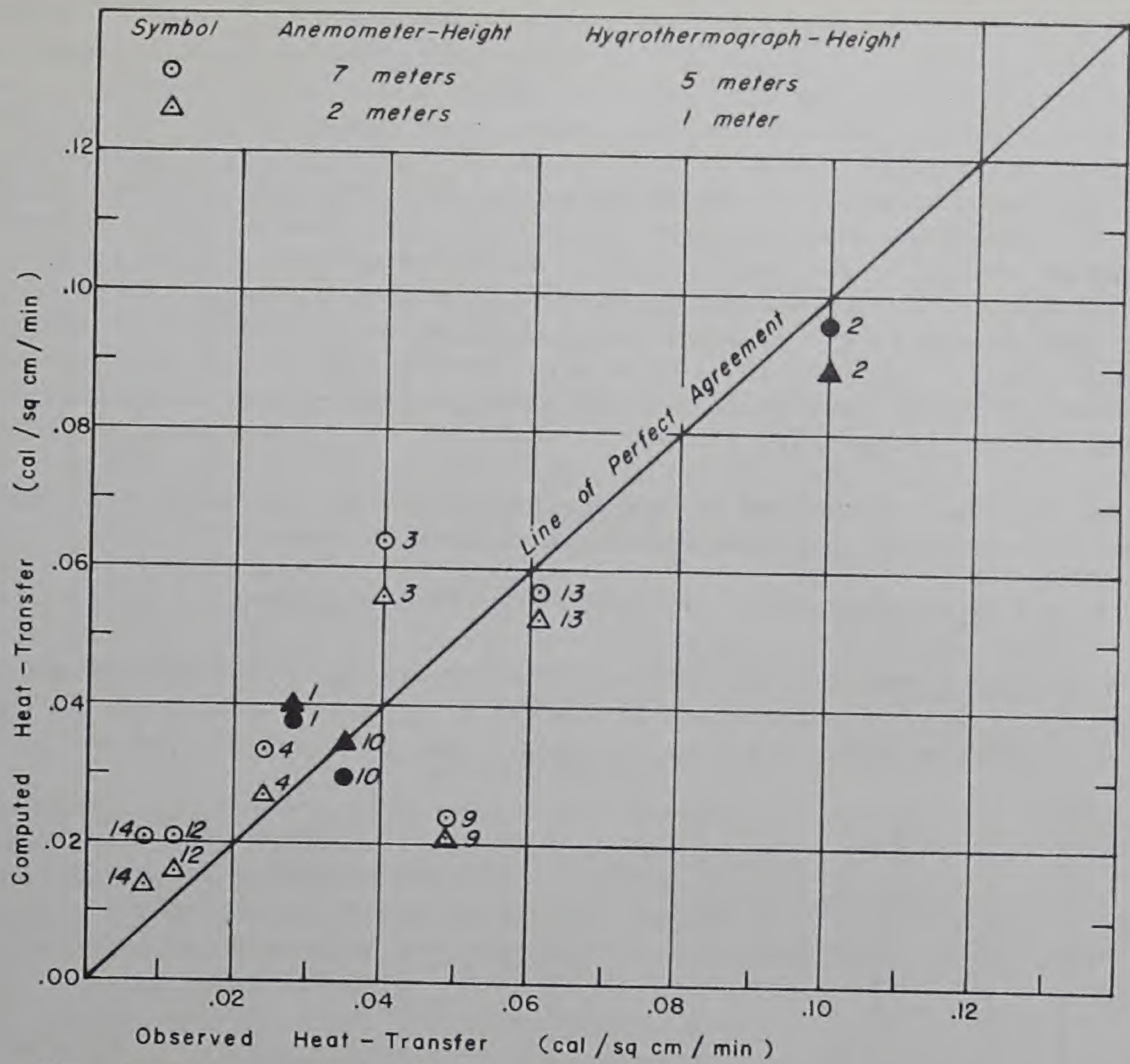

Fig. 4--Computed heat-transfer versus observed heat-transfor for various melting periods

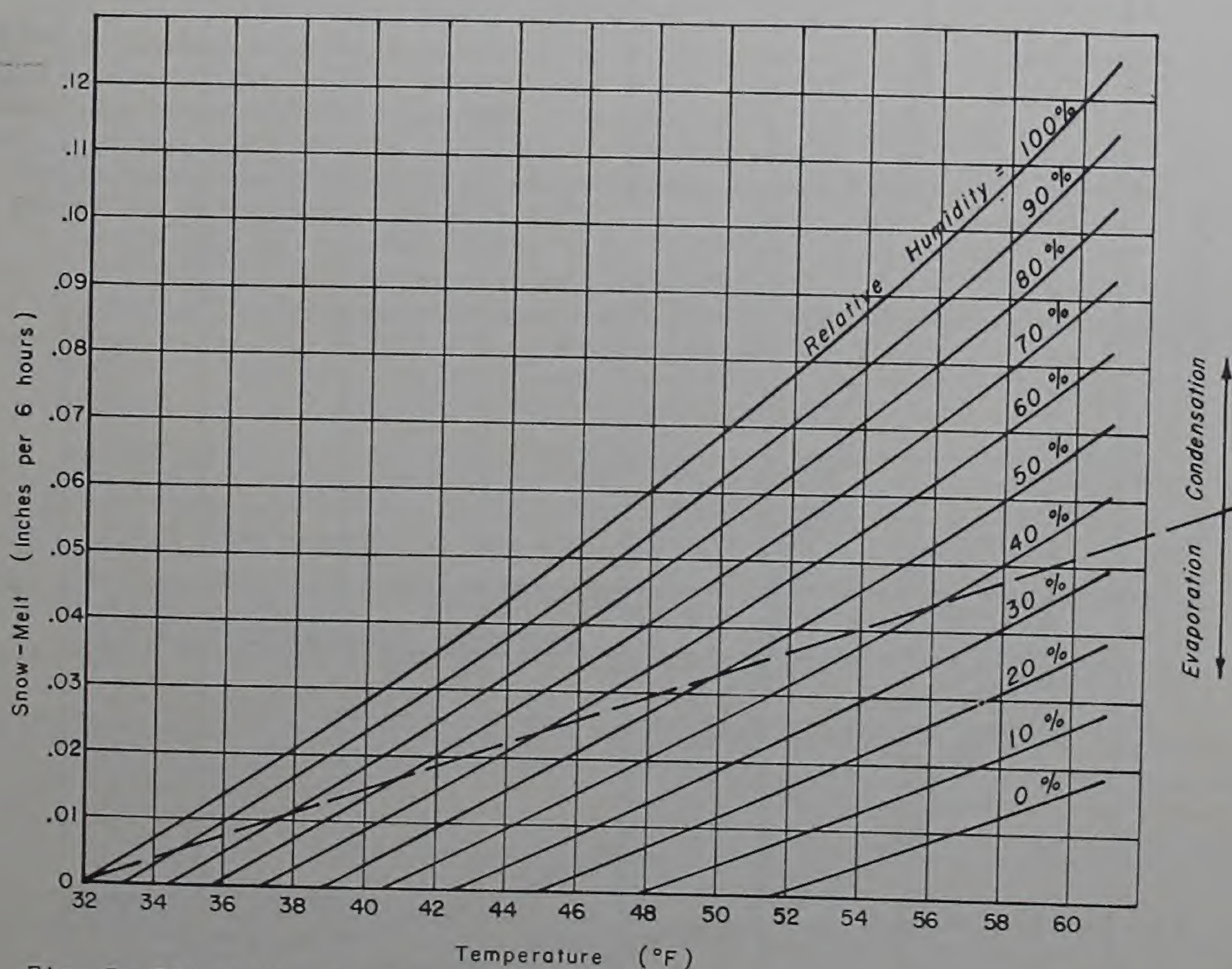

Fig. 5--Effective snow-melt due to turbulent exchange for unit wind-velocity

As a further check on the applicability of the theory, separate sets of computations were made of total heat-transfer for each period plotted in Figure 2 by means of equations (2) and (3), using two different levels of observations. These values are plotted against observed values of heat-transfer in Figure 4, and reasonably close agreement may be noted for periods of relatively high wind-velocity. Other points, in general, show greater deviations between observed and computed values with a tendency towards agreement for computations based on observations at the lower levels. This indicates that equation (4) is applicable, within a reasonable limit of error, for ordinary levels of observations with conditions of moderate to strong wind-velocities, but for winds of lesser intensity, accuracy of the formula is dependent on closer proximity of instruments to the snow-surface. It should be emphasized at this point that the formula is presented as an approximate relation, to be used when observations at a single level only are available. For greater accuracy, particularly in the case of light winds, it is necessary to make use of turbulence formulae requiring records for at least two levels above the snow-surface.

By adopting reference-elevations of instruments of a = 50 feet and b = 10 feet, it is possible to reduce the expression for snow-melt to a simplified form.

$$D = U_m\,[0.00184\,(T_f - 32)\,10^{-0.0000156h} + 0.00578\,(e - 6.11)] \qquad (5)$$

where D is the effective snow-melt in inches per six hours, U_m is the average wind-velocity in miles per hour, T_f is the air-temperature in degrees F, e is the vapor-pressure in millibars, and h is the station-elevation above sea-level in feet. The station-elevation correction in the

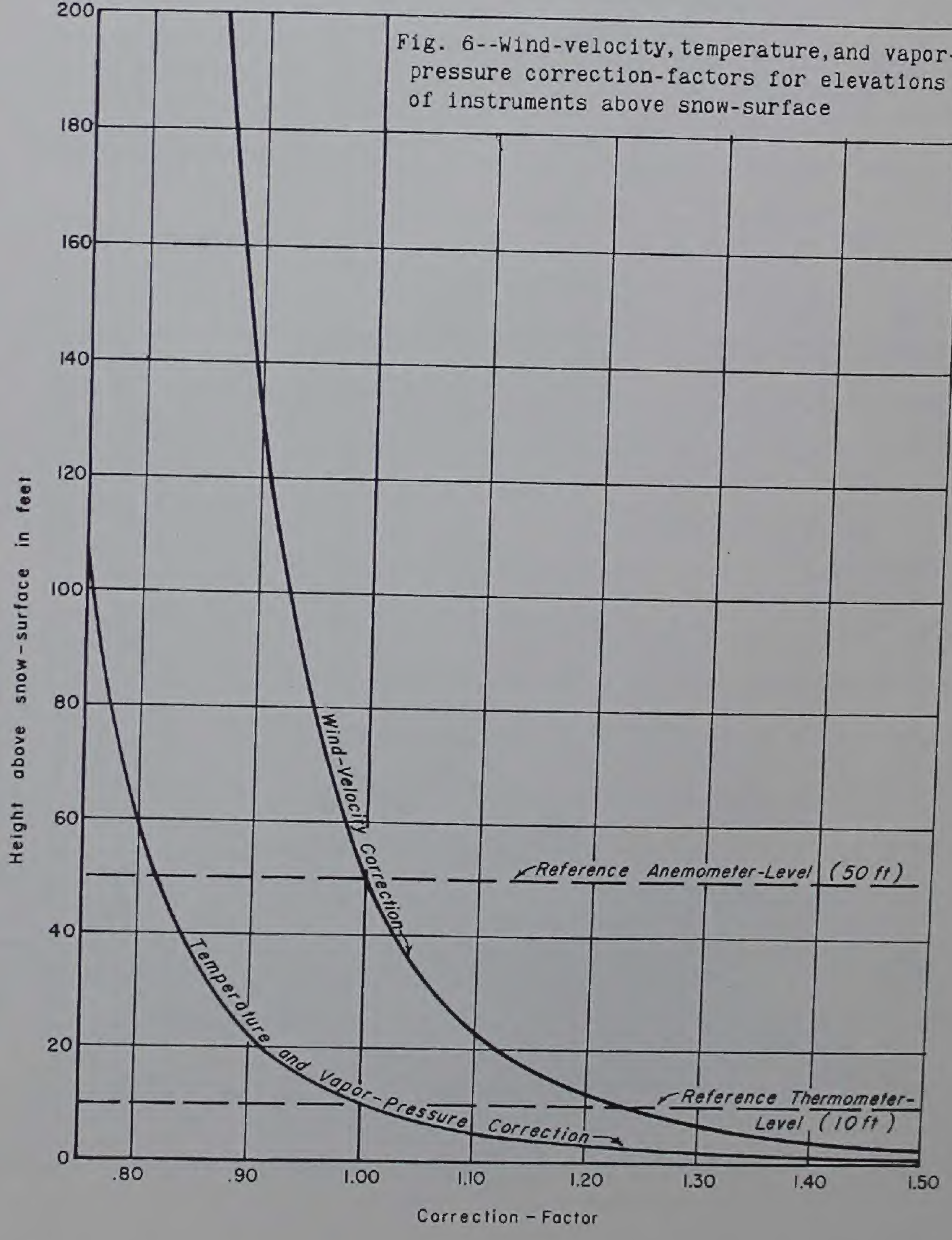

Fig. 6--Wind-velocity, temperature, and vapor-pressure correction-factors for elevations of instruments above snow-surface

final formula is based on a simple relation between atmospheric pressure and elevation which is sufficiently accurate for the purpose. By neglecting the elevation-factor, working curves shown in Figure 5 have been developed for application to lowland drainage-basins, giving snow-melt as a function of temperature and relative humidity for a unit wind-velocity. Melting rates are a linear function of wind-velocity so that values read off the curves are simply multiplied by the observed wind-velocity. In connection with the melting curves, a graph is shown in Figure 6 whereby observations at the actual levels may be corrected to the reference-elevations of instruments that form the basis for these curves. The adjustments are applied directly to wind-velocity, but for temperatures, corrections are made to the quantity (T - 32), and for vapor-pressures, corrections are made to the value (e - 6.11).

The curves of Figure 5 have been drawn for negative as well as positive values of the vapor-pressure gradient, and the assumption has, therefore, been made that the logarithmic law also applies to evaporation from snow. The boundary between condensation and evaporation is denoted by a dashed line while the balance between evaporation-loss and heat-gain by convection is represented by the zero melt-axis. It is noteworthy that air-temperatures up to 51° F are possible without the occurrence of melt, if the air is sufficiently dry. For higher elevations, the evaporation-term in the formula becomes more dominant and still greater temperatures are possible without melting. This is in accord with experience since it has been noted that late in the melting season the influx of warm air over mountainous watersheds will at times reduce the snow-cover at the upper elevations with little or no resulting runoff.

Effect of variations of elevation

In applying theoretical melting rates over a drainage-basin consideration must be given to changes in the air produced by differences of elevation in various portions of the basin-area. For a homogeneous air-mass the decrease in dry-bulb and dew-point temperatures with increase of elevation is related to the dry-adiabatic lapse-rate for unsaturated air and to the pseudo-adiabatic lapse-rate for saturated air. These rates are fairly constant with elevation and temperature and can be summarized as follows:

Unsaturated air:	Dry-bulb temperature decreases 5°4 F per 1,000 feet
	Dew-point temperature decreases 1°0 F per 1,000 feet
Saturated air:	Dry-bulb temperature decreases 3°0 F per 1,000 feet
	Dew-point temperature decreases 3°0 F per 1,000 feet

For lowland drainage-basins of level topography, observations of dry-bulb and dew-point temperatures can be corrected to the mean elevation of the basin and average melting rates determined to a sufficient degree of accuracy on the assumption of uniform wind-velocity in the region. Mountainous watersheds with large variations in elevation necessitate a division into melting zones with separate melt-computations for each zone. However, wind-velocity at a valley observation-station may not be representative of conditions at the higher elevations and considerable approximations may be involved in the calculations of melt for the upper zones. The procedure is illustrated in the area-elevation curve for the Big Cottonwood Basin, Figure 7. Here the Basin is subdivided into five zones of equal area and the vertical scales on the right-hand side give the dry-bulb and dew-point temperature reductions for each zone to be applied to observations at Salt Lake City Airport, a station near the Basin.

The following table illustrates the method of estimating average temperature-conditions in each melting zone from observations at the valley-station. Hypothetical dry-bulb and dew-point temperatures at Salt Lake City of 60° and 40°, respectively, are selected.

	Salt Lake City	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Dry-bulb	60	43	36	34	33	30
Dew-point	40	37	36	34	33	30

The dry-adiabatic lapse-rate is followed from the station to zone 2 where the dry-bulb and dew-point temperatures coincide. From that point, for the remaining zones, cooling proceeds along the saturated lapse-rate.

Effect of air-trajectory over snow

Loss of heat and gain or loss of moisture by warm air as it travels over the snow causes variations in temperature and humidity along the air-trajectory. This produces a continuous reduction in the melting power of the air from the snow-line into the interior of the snow-field, an effect that must be taken into account for a watershed of large areal extent. In order to

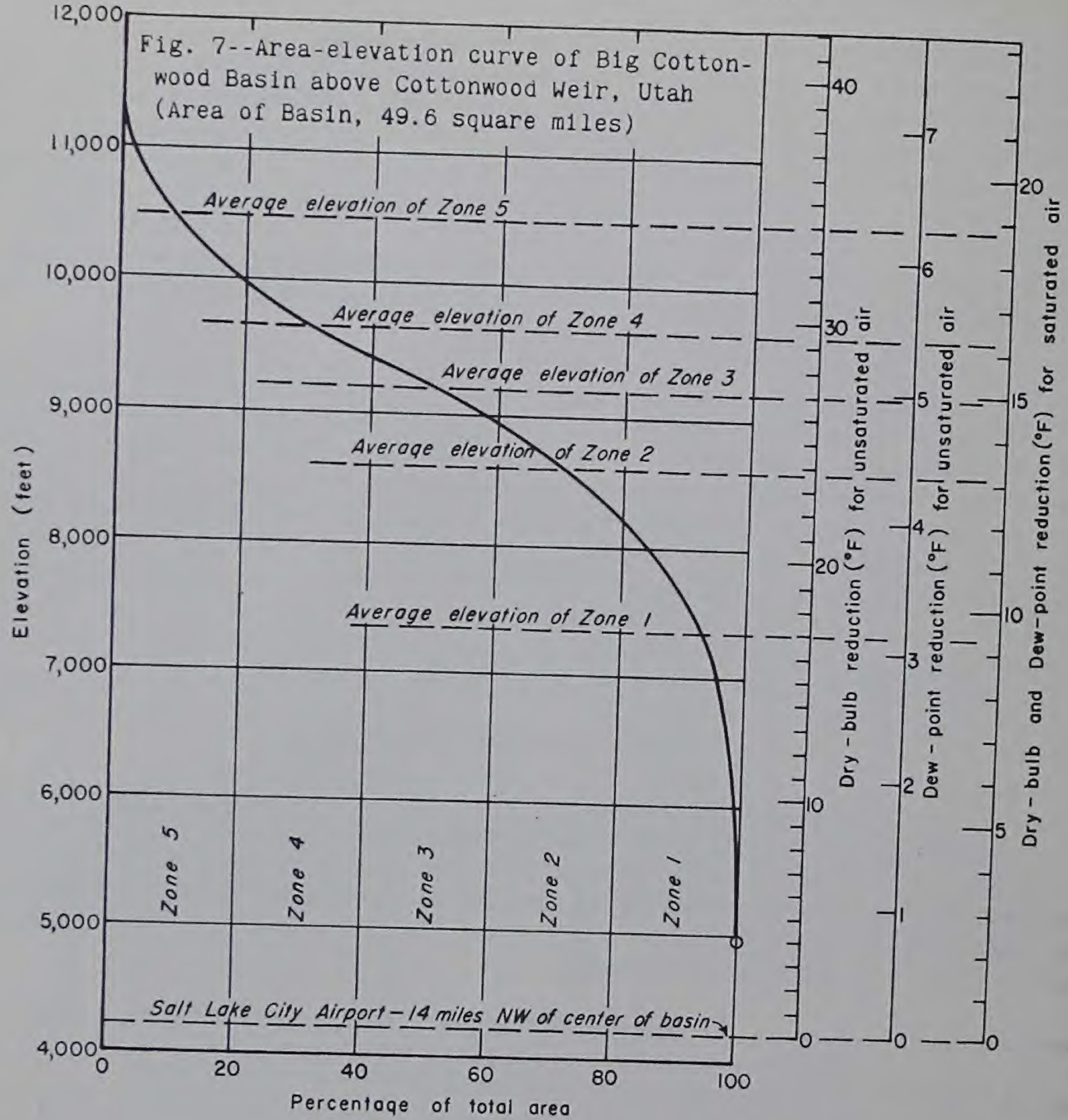

Fig. 7--Area-elevation curve of Big Cottonwood Basin above Cottonwood Weir, Utah (Area of Basin, 49.6 square miles)

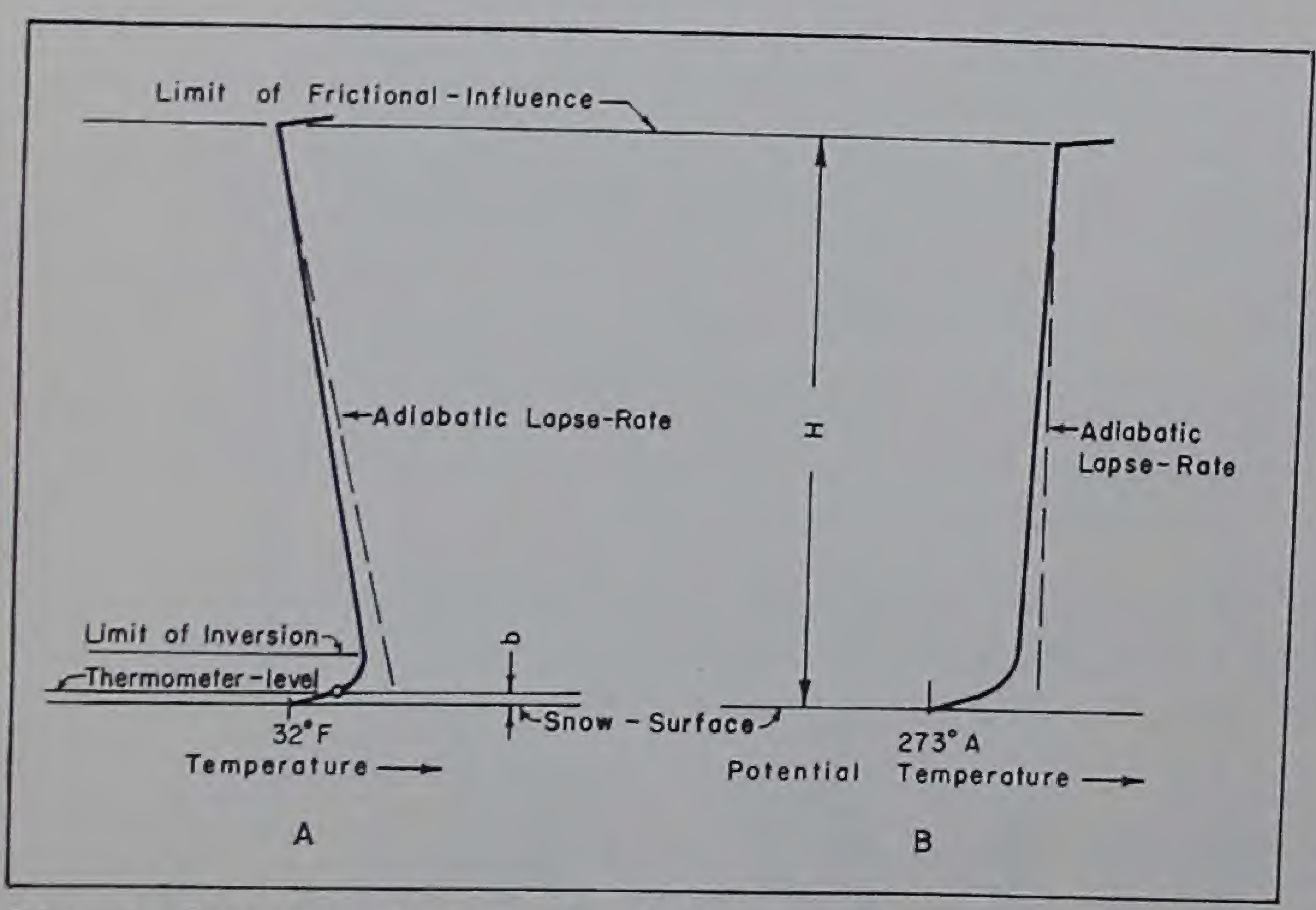

Fig. 8--Temperature and potential-temperature distribution above a melting snow-surface

compute the rate of temperature-decrease and increase or decrease of humidity with length of air-travel, the thickness of the turbulent layer of air as well as the distribution of elements throughout this layer must be known. Very few data of this sort are available and so the writer has attempted to estimate the cooling and drying or moistening effect through an analysis involving the use of certain simplifying assumptions.

Available upper-air soundings of warm turbulent air over snow were examined and showed the characteristic vertical temperature-distribution illustrated in Figure 8A. At the bottom of the turbulent layer a shallow temperature-inversion is formed that extends well above the ordinary thermometer-level. The temperature reaches a maximum and then begins to decrease with height at a rate approaching the adiabatic lapse-rate up to the limit of turbulent influence, which is marked by the formation of a second inversion. Near the surface, the temperature-gradient determines the quantity of heat-flow, but for large vertical sections of the atmosphere, the potential temperature-gradient is the governing factor in heat-transport. An adiabatic lapse-rate corresponds to a line of constant potential temperature and hence converting the temperature-distribution into one of potential temperature as shown in Figure 8B, it is seen that the potential temperature-gradient

is directed downward throughout the turbulent layer. Therefore, the total height of the turbulent layer, labelled H in the Figure, represents the column of air involved in transmitting heat to the snow. Since the processes of heat- and moisture-transfer are the same, the specific-humidity distribution is similar to the potential temperature-distribution and the height of the turbulent layer also determines the quantity of air involved in transmitting moisture to the snow.

Rossby has developed the following formula for the height of the frictional or turbulent layer in an adiabatic atmosphere:

$$H = \frac{246\ U}{\sin L\ \log(a/z_0)} \tag{6}$$

where L is the latitude in degrees. Stability dampens turbulence and hence will act to reduce the height of turbulent influence. However, on the basis of the temperature-distribution assumed here, the major portion of the turbulent layer is close to a state of adiabatic equilibrium and, therefore, to an approximate degree, equation (6) is still applicable. For middle latitudes, this relation can be expressed roughly in terms of wind-velocity if we assume a latitude of 40° and substitute for the reference-anemometer elevation of 50 feet

$$H = 124\ U \tag{7}$$

If we let θ equal the average potential temperature of the layer, then the heat-content of a column of dry air, E, is given approximately by

$$E = c_p\rho\theta H = 124c_p\rho U\theta \tag{8}$$

Referring to equation (2), the rate of heat-loss to the snow is

$$(dE/dt) = -k\ \frac{c_p\rho k_o^2}{\ln(a/z_0)\ln(b/z_0)}\ UT \tag{9}$$

where k is a constant that includes the effect of basin-characteristics on the average rate of transport. The value of this constant for the Upper Ohio Region is 0.65, determined by an empirical method to be described shortly. Substituting for z_0, k_0, and the reference-elevations of instruments

$$(dE/dt) = -0.00232kc_p\rho UT \tag{10}$$

Differentiating (8) with respect to time with ρ approximately constant and equating to (10)

$$124c_p\rho U d\theta/dt = -0.00232kc_p\rho UT \tag{11}$$

At this point the assumption is made that cooling results in a uniform decrease of temperature along the vertical axis. This is a simplification which appears reasonable for a short distance of travel or time-interval.

Then

$$(d\theta/dt) = (dT/dt) \tag{12}$$

and

$$(dT/dt) = -1.89kT \times 10^{-5} \tag{13}$$

The average velocity of the frictional layer may be taken as equal to the gradient-wind velocity. The proportionality-factor between surface- and gradient-wind depends mainly on the roughness-parameter. Hence, for a value of 0.25 cm for the roughness-parameter, there is a fairly constant ratio between surface- and gradient-wind. From graphs developed by Rossby

$$\text{Gradient-wind velocity} = 1.56U \tag{14}$$

By use of the above relation, equation (13) can be converted into an expression giving the temperature-reduction per unit-distance of air-travel along the snow-cover.

$$(dT/dx) = -0.0437k(T_f - 32)/U_m \tag{15}$$

where T_f is temperature in degrees F, x is distance in miles, and U_m is wind-velocity in miles per hour.

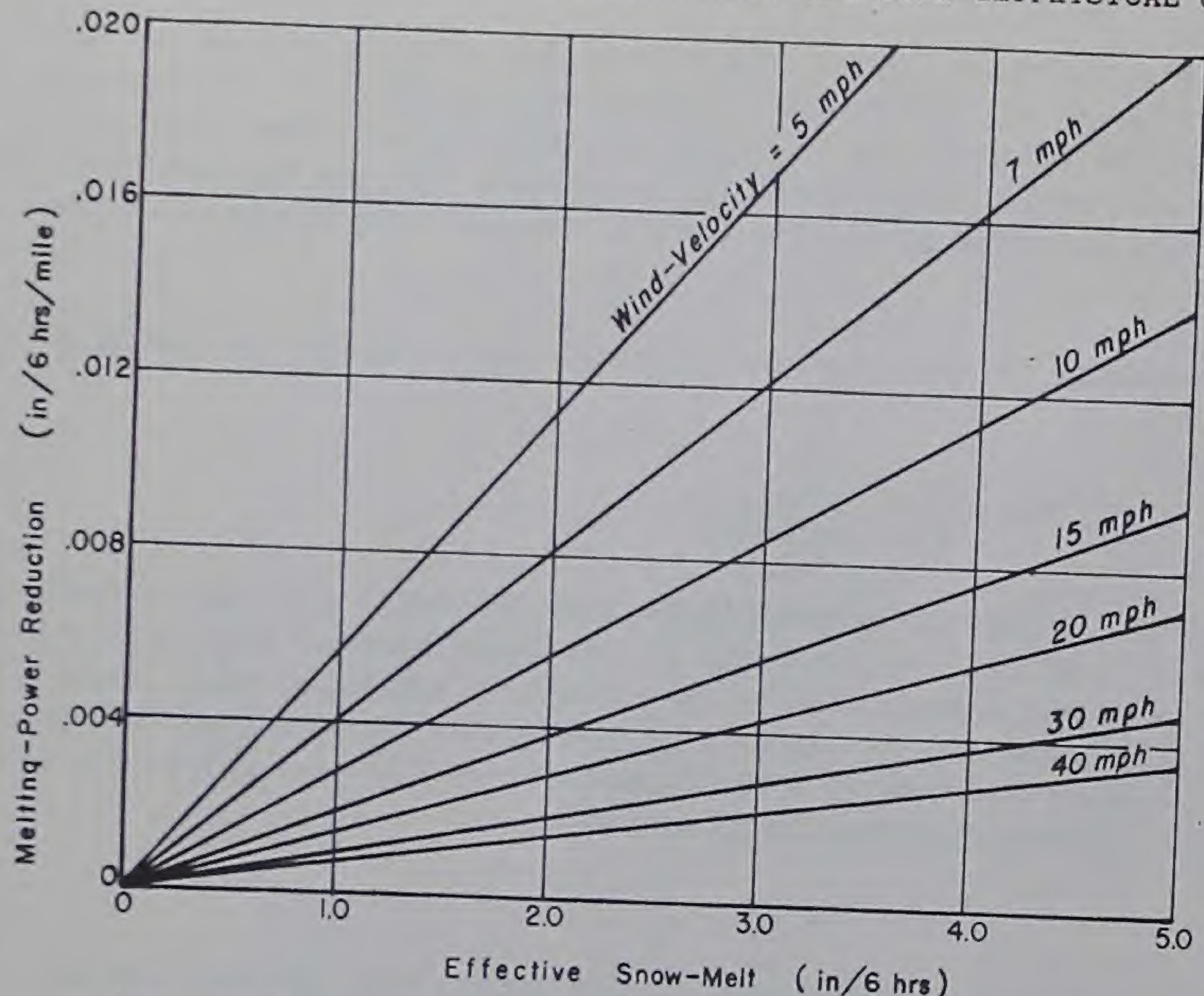

Fig. 9--Reduction of melting power of air over snow

The same procedure can be used to obtain the rate of drying or moistening of the air as it traverses the snow-surface. The reasoning here is that the specific humidity and potential temperature-distributions are analogous and a similar assumption can be made regarding the change in specific humidity at a particular level. Hence the formula for rate of change of specific humidity is the same as that of temperature, and

$$(dq/dx) = -0.0437k(q-q_o)/U_m \quad (16)$$

where q is the specific humidity of the air in g/kg and q_o is the saturated specific humidity at 32° F in g/kg.

On the basis of equations (15) and (16), curves have been developed, shown in Figure 9, giving the decrease in the melting power of warm air per unit-distance of air-travel along a melting snow-field. These curves, together with corrections for elevation-differences discussed previously, are presented as a method of estimating melting factors for a drainage-basin from meteorological observations in the immediate vicinity of the watershed.

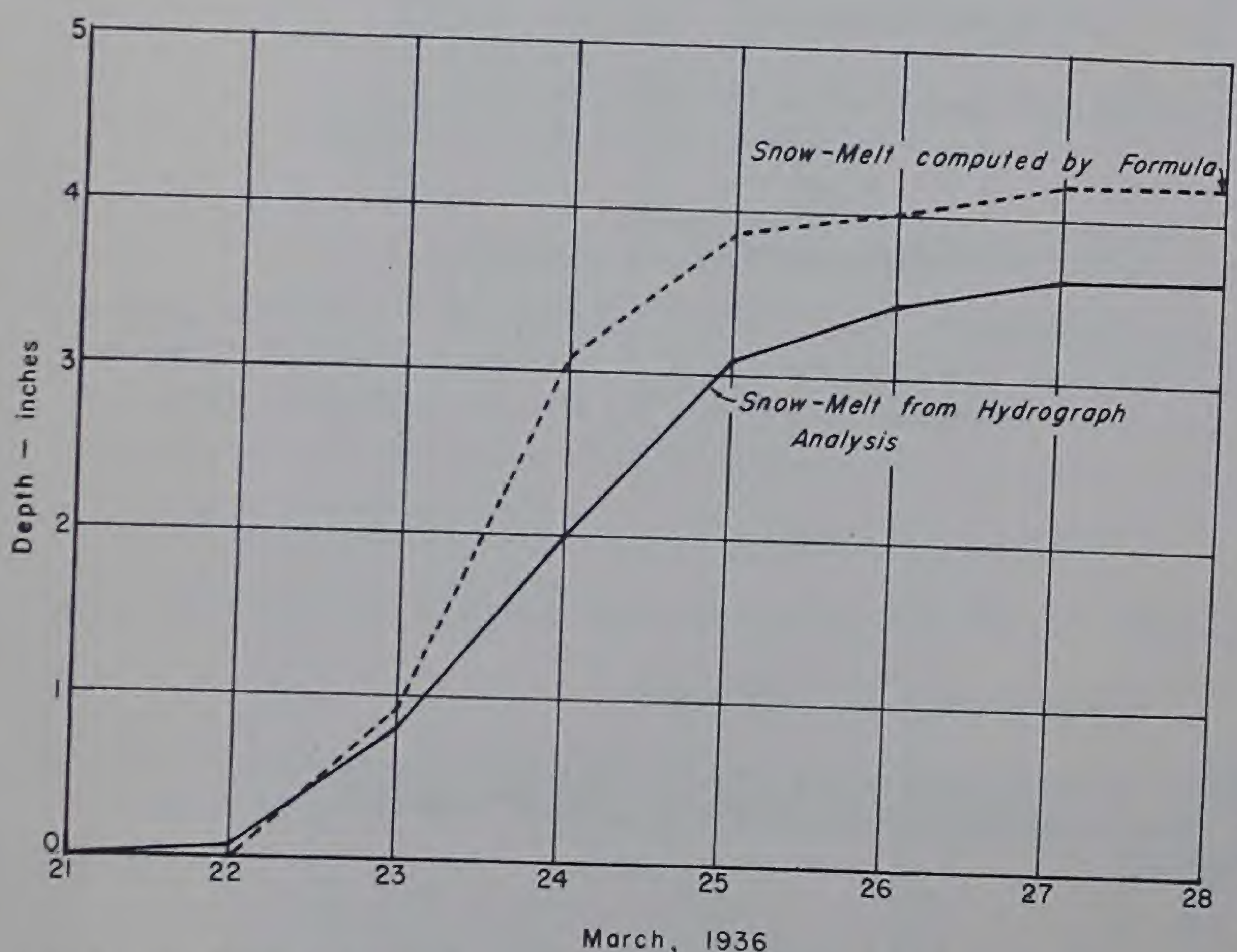

Fig. 10--Mass-curves of snow-melt for French Creek Basin at Saegerstown, Pennsylvania (629 square miles), March 21-28, 1936

Basin melting rates

In applying theoretical point snow-melt rates to an actual drainage-basin, consideration must be given to two modifying factors. One is the surface-roughness, which may vary from basin to basin, but always exceeds the roughness of a level snow-field. Another factor is the type and percentage of forest-cover within a basin. It is a well-known fact that snow-melt rates in a forested area are considerably less than melting rates in non-forested areas. The frictional effect of trees serves to reduce the wind-velocity and hence decreases the intensity of turbulence underneath the forest-canopy. However, sufficient data are not available by means of which a general formula may be applied to evaluate this reduction in turbulent transport.

The method adopted was to group the two effects of surface-roughness and forest-cover into a single constant so that

$$\text{Basin snow-melt} = kD \quad (17)$$

To establish the value of k for an individual basin it was necessary to correlate observed snow-melt with theoretical snow-melt obtained by use of the formula submitted in the paper. In general, it can be stated that the value of k should be less than one. The effect of increased

roughness is to raise the rates of melt above the values given by the formula. However, it is the small-scale roughness and not the broad topographic features of the basin that influences turbulent exchange. The effect of drifting of snow is to smooth out the basin-surface, and hence the roughness-parameter assumed here may not differ greatly from that over an actual basin. Therefore, it seems reasonable to expect that the influence of forest-cover exceeds that of surface-roughness and in general, the actual snow-melt should be less than the theoretical melt. The theoretical formula sets an upper limit of melting for a given meteorological situation, or, in other words, gives values that apply for the ideal condition of a flat basin, uniformly covered with snow, and without surface-obstructions.

Conclusions

As mentioned previously, k has a value of 0.65 for the Upper Ohio Region. A study of several hydrographs of rapid snow-melt for various sub-basins in the Upper Ohio Watershed showed fairly uniform values for the melting constant, justifying its use as a general constant for the entire Region. In each case, theoretical melting was computed after correcting observations at the nearest regular Weather Bureau station by the method outlined above. Observed snow-melt was obtained by subtracting total rainfall from total surface-runoff during the melting period, and the melting constant k determined by dividing the observed by the theoretical melt. To illustrate the application of this method, mass-curves of melt computed by means of the formula and modified by the empirical constant together with melt obtained by runoff-analysis are shown in Figure 10 for the period March 21-28, 1936, in the French Creek Basin at Saegerstown, Pennsylvania. Meteorological observations at Erie, Pennsylvania, were used to compute the melting factors.

Too many approximations are involved in the determination of snow-melt from discharge-records to claim full verification of the theory on the basis of the limited amount of data analyzed thus far. A thorough check would require complete data of snow-depletion in a particular drainage-basin with simultaneous meteorological observations at several locations in the watershed during a period of rapid melt.

Acknowledgments--The writer gratefully acknowledges assistance rendered by Walter T. Wilson and Ray K. Linsley, and aid in preparation of the manuscript by Herbert C. S. Thom.

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U. S. Weather Bureau,
Washington, D. C.

FORECASTING THE DATE OF THE DECLINE OF THE CARSON RIVERS ON THE BASIS OF THE SEASONAL PERCENTAGE OF THE CONTRIBUTING SNOW-COVER

Peter Krummes

(Contributed for its practical suggestions where adequate storage is lacking)

On account of not having enough water-storage on the upper region of the Carson rivers, the water-users here are not so much interested in the runoff in acre-feet for the season. The important thing is the discharge of the rivers in second-feet on certain dates.

By your snow-survey reports of April 1, and the records of river-discharge in second-feet, I have attempted to make such a forecast.

In the spring of 1939 a few farmers asked me what priority rights I thought could be served with water through that season, or, rather, what land I thought would be safe to plant to young alfalfa in that season. The only way I could answer that was to go to the results of the April 1 snow-survey, take the percentage of normal of that year, then go back to another year of nearly the same percentage and see what happened in that year as to dates of certain river-discharge.

By this means I predicted that the river would drop to 200 second-feet on a certain date. It dropped to 200 second-feet five days after the date I predicted. Last year (1940) it dropped to 200 second-feet ten days sooner than I had predicted. But May was an unusually hot month last year, and brought the water down sooner than a normal May would have.

Past records as to snow-survey at Blue Lakes and dates of discharge of East Fork of Carson River at Horseshoe Bend are as follows:

Snow percentage of normal, April 1	Date river-discharge dropped to 200 sec-ft
1929- 40	July 7
1930- 63	July 12
1931- 37	June 7
1932-101	August 1
1933- 61	July 14
1934- 29	No record
1935- 63 (Apr. 1) but 85 (April 20)	August 1, 131 sec-ft (no record of 200 sec-ft)
1936- 99	July 25
1937- 83	July 10
1938-122	August 10, 221 sec-ft (probably 200 sec-ft about Aug. 16)
1939- 47	June 22, 195 sec-ft
1940- 95	July 13

In the years 1934 and 1935 I was on the Humboldt River in Elko County the entire season, and no complete records for these years were kept on the Carson River.

These records will give some idea as to the requirements and possibilities here.

Alpine Land and Reservoir Company,
Gardnerville, Nevada

DISCUSSION

H. P. BOARDMAN (Nevada Cooperative Snow-Surveys, Reno, Nevada)--On the basis of snow-cover, precipitation during autumn and spring, and temperature during melting, the graph of Figure 1 has been prepared showing the ideal relationship of the snow-cover at Blue Lakes to the date of the 200 second-feet discharges of the East Fork of the Carson River and variations between the expected date and actual.

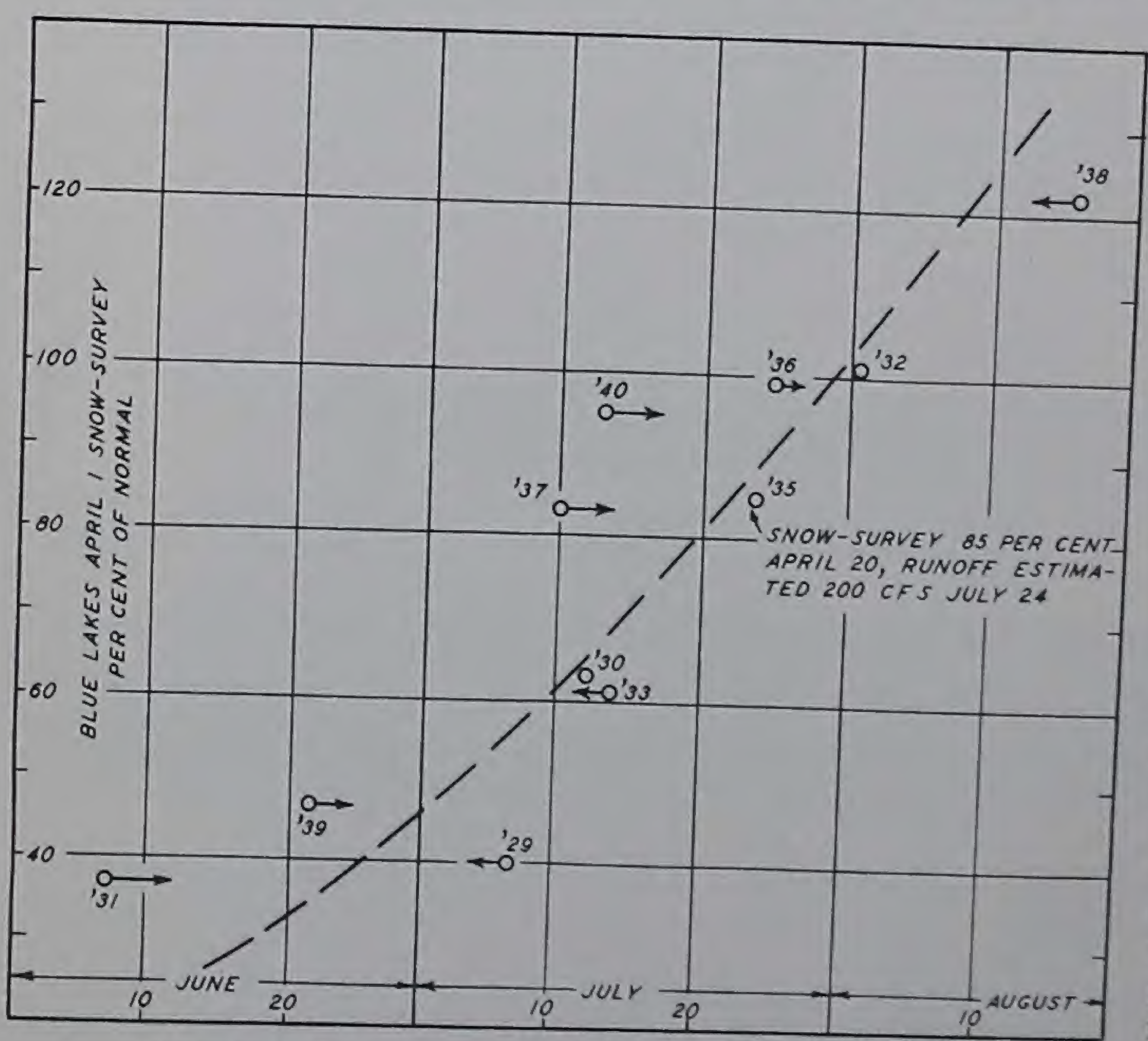

Fig. 1--Dates when runoff of East Carson River at Horseshoe Bend decreases to 200 cfs

Referring to the graph representing the above relationship, an attempt will be made to explain some of the points which do not fall close to the line.

In general, unusually high average temperature for the month of April, May, or June, and especially for the month of May have a tendency to carry off the melting snow earlier than normal and hence to make the date when the discharge decreases to 200 cfs come earlier than normal, and likewise when the month of May in particular is abnormally cold the runoff will be decreased below what should have been expected from the snow-cover as of April 1.

Arrows pointing to right or to left in Figure 1 indicate the direction in which the point would probably be moved if conditions other than the water-content in the snow had been practically normal. The discussion of the points on the graph will be taken up starting with the low percentage years and progressing toward the maximum year.

1931--High temperature both April and May and resulting early runoff.

1929--Rather high May temperature, 3° to 4° F above normal, but quite heavy precipitation in June.

1939--April temperature was 5° to 6° F high and May temperature a little above normal.

1933--Very low temperature in May, 6° to 8° F below normal and above normal May precipitation.

1930--May temperature about 4° F below normal; June temperature about the same amount above normal; spring precipitation rather high.

1937--Very deficient precipitation in the previous fall thus increasing absorption-losses from the spring runoff; rather high May temperature.

1935--Very heavy precipitation of snow during the first half of April and snow-surveys of April 20 indicated 85 per cent of normal but very little precipitation occurred after April 16. The estimated date for 200 cfs runoff is July 24.

1940--High temperature, 4° to 6° F above normal, in both May and June, must have been the reason for the early runoff.

1936--Temperature a little above normal in April and May.

1932--Fairly normal in most respects.

1938--Spring temperatures approximately normal but flood-rains during the previous December must have increased ground-storage and prolonged the runoff-period.

It has been customary for the Forecast Committee for a number of years to estimate the date when the natural flow of the Truckee River, exclusive of Tahoe, will probably fall to 500 cfs and also to estimate the date of maximum elevation of Lake Tahoe.

Business Meeting

Fred H. Paget, presiding

The Business Meeting was held at Traveler's Hotel as part of the Dinner Session of the Western Interstate Snow-Survey Conference. The session was planned and conducted by the South Pacific section of the Executive Committee consisting of Fred H. Paget, Chairman, H. P. Boardman, James E. Jones, Joseph Kittredge, Jr., and William A. Lang. Mr. Lang was local chairman of the session and Mr. Paget, as Chairman of the General Executive Committee, presided at the Business Meeting. Number present was 100.

Of the General Executive Committee a majority were present despite the wide extent of the area covered by the general conference. These were:

North Continental Divide--James C. Marr and Lynn Crandall.
North Pacific Coast--R. A. Work and Phil E. Church.
South Continental Divide--Ralph L. Parshall, Harry L. Potts, and Ashton C. Codd.
South Pacific Coast--Fred H. Paget, H. P. Boardman, James E. Jones, and William A. Lang.

The complete personnel list of the Executive Committee is given in the Transactions of 1940 [pp. 1052-1053]. However, during the absence for military service of George G. West, Chairman of the North Pacific Coast Area, and R. C. Farrow, Norbert Leupold, United States Army Engineers at Portland, and S. H. Frame, Water Rights Branch of British Columbia, have been chosen in their places. R. A. Work has been selected regional chairman.

Purpose and organization--The formal activities of the Conference consist of regional meetings for the presentation of reports and the discussion of problems connected with snow and ice. The division into four areas is for the purpose of developing the Conference in all sections of the Western States while maintaining its essential unity. Therefore, the Executive Committee, consisting of 20 members, is chosen by the entire Conference and acts as a unit. However, each area is assured of its one-fourth of the membership of the Committee to supplement the general administration by special suggestions. A general chairman directs the entire Committee while subchairmen direct the regional groups. While feasible, meetings are held in affiliation with the regional meetings of the Section of Hydrology of the American Geophysical Union, whose western areas are identical with those of the Conference.

The membership of the Conference consists of those who have attended the meetings of the Conference or have been accepted into membership by the Executive Committee. Membership with privilege of voting also belongs automatically to all organizations that support snow-surveying and the activities of the Conference by money, equipment, or personnel.

The privilege of discussion and voting belongs to all members irrespective of regional division.

Questions and amendments may be initiated at any regional meeting or by the Executive Committee but must be referred for final adoption to the general membership.

Amendments--It was proposed that each of the four areas be empowered to elect its own representatives on the Executive Committee on the ground that members were insufficiently familiar with candidates outside their own area to choose wisely.

Since the areas with smaller membership had no fear of domination by the larger and older South Pacific Coast Area, but welcomed its experience and leadership, it was decided to keep the Conference as closely unified as possible.

To increase the power of initiative, however, it was proposed to give one-fourth of the members of the Executive Committee authority to bring questions before that body for decision and enactment in case of the Chairman's inability or unwillingness to act. Discussion of this amendment was barred by a previous decision to make no changes in the By-Laws at this time.

Retrenchment--There was a strong feeling that retrenchment in amount of published matter and mailing list should be attempted to meet the cost of printing in the Transactions of the American Geophysical Union and circulation.

The large amount of publication during the year had been caused by the two meetings, namely, at Stanford University and the University of Washington, and the large program of the latter. The size of the mailing list was due to active response to the new plan of electing members without actual attendance at the conferences and to the desire of others to be placed on the mailing list. Despite the elimination of all who did not fill out the revision questionnaire, the circulation remained at approximately 1,000.

The support for publishing the Transactions of the Conference had long been obtained through the sale of copies to organizations for distribution to their personnel. A total of 2,600 copies have thus been placed in circulation with resulting growth in interest in snow-surveying and progress in the solution of attendant problems. The copies have been distributed free.

The size of the Transactions of the Conference thus far had been fully justified by the pioneer character of snow-surveying and the need of interchange of experience. However, it was now proposed that only one large program be developed each year, and that other programs be restricted to dinner or business meetings.

It was further proposed that contributions or memberships of $1.00 be considered as a supplemental source of income. This problem was left for the Executive Committee in case the present income fell below requirements.

Mimeograph copies of the membership and mailing list were promised for use in avoiding duplication in distributing copies of the Transactions and placing in the hands of supporting organizations the names of their personnel who are now on membership or mailing lists of the Conference.

The income for the two years of 1940 and 1941 should balance all obligations and provide free copies of Transactions to the members. The financial management was transferred during the year by Dr. J. E. Church and Carl Elges to the Chairman of the Executive Committee as his future natural task. A detailed financial statement for the two years will be presented by him at the next meeting.

Policy and research--In line with the recommendation in Mr. Conkling's introductory address, a Committee on Policy and Research was authorized to indicate trends of snow-survey interest and subjects for investigation and report at future meetings.

The motion as passed was as follows: "That the Chairman of the Executive Committee of the Western Interstate Snow-Survey Conference appoint a Committee to investigate the past results achieved in runoff forecasting in the Western States and Provinces through application of the science of snow-surveying, and also make further investigations with a view to formulating suggestions or plans for desirable research work in field or office which might prove beneficial for future snow-survey activities."

The following members of the Committee were appointed and have accepted: J. E. Church, Chairman; Merrill Bernard; George D. Clyde; Joseph Kittredge, Jr.; R. L. Parshall; and R. A. Work.

Other snow-conferences--A letter was read from Merrill Bernard announcing the formation of the Eastern Snow-Conference at Harvard University, September 16, and the Great Lakes or North Central States Snow-Conference at Detroit, Michigan, December 12, and suggesting that a National Convention be held some day. E. S. Cullings, Secretary, Black River Regulating District, Watertown, New York, was chosen Chairman of the Executive Committee of the former and M. W. Kyler, Wisconsin Valley Improvement Company, Wausau, Wisconsin, was chosen Chairman of the latter.

In the Eastern Snow-Conference, a research committee, manned by G. A. Hathaway, United States Army Engineers, Washington, D. C.; C. F. Merriam, Pennsylvania Water and Power Company, Baltimore, Maryland; and J. S. Sweet, United States Weather Bureau, Albany, New York, had already begun vigorous activity in the thermodynamics of snow.

Coming meetings--Following the initiative of the Executive Committee of the Section of Hydrology of the South Pacific Area, which now holds meetings annually, a Snow-Survey Conference was announced provisionally for January, 1942, at the California Institute of Technology at Pasadena. However, since a meeting was being planned by the Section Committee of the South Continental Divide at Salt Lake City in the summer of 1942, it was decided to hold a formal conference there and restrict the Pasadena Conference to a dinner meeting and business session.

Distribution of membership

Area	Members	Member organizations	Total
North Continental Divide	94	30	124
South Continental Divide	97	29	126
North Pacific Coast	76	30	106
South Pacific Coast	247	55	302
None specified	19	10	29
Totals	533	154	687

List of member organizations

A member organization is one that aids the snow-survey work either financially or with its field-personnel. An organization is an administrative unit, such as Federal, State, District, Section-center, national forest, national park, irrigation-project, power-company, agricultural or forest experiment station, etc. Member organizations, like individual members, are granted one ballot each.

North Continental Divide Area

Associated Ditch Companies, Joseph, Oregon
U. S. Army Engineers, Missouri River Division, Kansas City, Missouri
City of Bozeman, Bozeman, Montana
Commissioner of Reclamation, Boise, Idaho
Dominion Water and Power Bureau, Calgary, Alberta, Canada
Eastern Oregon Light and Power Company, Baker, Oregon
U. S. Forest Service, Regional Office, Missoula, Montana
Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana
U. S. Geological Survey, Water Resources Branch, Boise, Idaho
U. S. Fish and Wildlife Service, Burns, Oregon
U. S. Geological Survey, Water Resources Branch, Helena, Montana
U. S. Geological Survey, Water Resources Branch, Idaho Falls, Idaho
Idaho Power Company, Boise, Idaho
Division of Irrigation, U. S. Soil Conservation Service, Boise, Idaho

North Continental Divide Area--Concluded
City of LaGrande, LaGrande, Oregon
Montana Agricultural Experiment Station, Bozeman, Montana
Montana State Engineer, Helena, Montana
Montana State Planning Board, Helena, Montana
North Montana Branch Station, Havre, Montana
Portland General Electric Company, Baker, Oregon
U. S. Indian Service, Boise, Idaho
U. S. Indian Irrigation Project, St. Ignatius, Montana
U. S. Bureau of Reclamation, Boise Project, Board of Control, Boise, Idaho
U. S. Bureau of Reclamation, Owyhee Project, Boise, Idaho
U. S. Bureau of Reclamation, Vale, Oregon
U. S. Weather Bureau, Boise, Idaho
U. S. Weather Bureau, Helena, Montana
Warmsprings Irrigation District, Vale, Oregon
Washington Water Power Company, Spokane, Washington
Yellowstone National Park, Mammoth, Wyoming

South Continental Divide Area
Colorado Agricultural Experiment Station, Fort Collins, Colorado
Colorado River Water Conservation District, Grand Junction, Colorado
U. S. Forest Service, Ashley National Forest, Vernal, Utah
U. S. Forest Service, Cache National Forest, Logan, Utah
U. S. Forest Service, Dixie National Forest, Cedar City, Utah
U. S. Forest Service, Fishlake National Forest, Richfield, Utah
Intermountain Forest Experiment Station, Ogden, Utah
U. S. Forest Service, Intermountain Region, Ogden, Utah
U. S. Forest Service, LaSal National Forest, Moab, Utah
U. S. Forest Service, Manti National Forest, Ephraim, Utah
U. S. Forest Service, Powell National Forest, Panguitch, Utah
U. S. Forest Service, Uinta National Forest, Provo, Utah
U. S. Forest Service, Wasatch National Forest, Salt Lake City, Utah
U. S. Forest Service, White River National Forest, Glenwood Springs, Colorado
U. S. Geological Survey, Water Resources Branch, Denver, Colorado
U. S. Geological Survey, Water Resources Branch, Salt Lake City, Utah
Division of Irrigation, U. S. Soil Conservation Service, Fort Collins, Colorado
Division of Irrigation, U. S. Soil Conservation Service, Logan, Utah
Ogden River Water Users Association, Ogden, Utah
Price River Water Commissioner, Price, Utah
Bureau of Reclamation, Denver, Colorado
Utah Agricultural Experiment Station, Logan, Utah
Utah Cooperative Snow-Surveys, Utah State Agricultural College, Logan, Utah
Water Commissioner, Spanish Fork, Utah
U. S. Weather Bureau, Albuquerque, New Mexico
U. S. Weather Bureau, Cheyenne, Wyoming
U. S. Weather Bureau, Denver, Colorado
U. S. Weather Bureau, Salt Lake City, Utah
Weber River System, Ogden, Utah

North Pacific Coast Area
The British Columbia Electric Railway Company, Ltd., Vancouver, B. C., Canada
City of Corvallis, Corvallis, Oregon
The California Oregon Power Company, Medford, Oregon
Central Oregon Irrigation District, Redmond, Oregon
City of The Dalles, The Dalles, Oregon
Deschutes County Municipal Improvement District No. 2, Bend, Oregon
East Kootenay Power Company, Ltd., Ferney, B. C., Canada
Leupold and Volpel, Instrument Makers, Portland, Oregon
Medford and Rogue River Irrigation District, Medford, Oregon
Pacific Power and Light Company, Portland, Oregon
Bonneville Power Administration, Portland, Oregon
U. S. Forest Service, Region 6, Portland, Oregon
U. S. Geological Survey, Tacoma, Washington
Oregon State Engineer, Salem, Oregon
U. S. Geological Survey, Portland, Oregon
Grants Pass Irrigation District, Grants Pass, Oregon

North Pacific Coast Area--Concluded

U. S. Indian Service, Klamath Indian Reservation, Klamath Agency, Oregon
Division of Irrigation, U. S. Soil Conservation Service, Medford, Oregon
Jordan Valley Irrigation District, Arock, Oregon
Lakeview Water Users Association, Lakeview, Oregon
Ochoco Irrigation District, Prinsville, Oregon
Oregon Agricultural Experiment Station, Corvallis, Oregon
Oregon State Highway Engineer, Salem, Oregon
U. S. National Park Service, Crater Lake National Park, Medford, Oregon
Powell River Company, Limited, Powell River, B. C., Canada
Puget Sound Power and Light Company, Seattle, Washington
U. S. Bureau of Reclamation, Klamath Falls, Oregon
Water Rights Branch, Department of Lands, Victoria, B. C., Canada
U. S. Weather Bureau, Seattle, Washington
U. S. Weather Bureau, Portland, Oregon

South Pacific Coast Area

Arizona State Water Commissioner, Phoenix, Arizona
State of California, Division of Water Resources, Sacramento, California
California Forest and Range Experiment Station, Berkeley, California
East Bay Municipal Utility District, Oakland, California
Elko-Lamoille Power Company, Elko, Nevada
U. S. Bureau of Entomology and Plant Quarantine, Berkeley, California
U. S. Fish and Wildlife Service, Cedarville, California
U. S. Forest Service, Eldorado National Forest, Placerville, California
U. S. Forest Service, Humboldt National Forest, Elko, Nevada
U. S. Forest Service, Inyo National Forest, Bishop California
U. S. Forest Service, Lassen National Forest, Susanville, California
U. S. Forest Service, Modoc National Forest, Alturas, California
U. S. Forest Service, Mono National Forest, Reno, Nevada
U. S. Forest Service, Nevada National Forest, Ely, Nevada
U. S. Forest Service, Plumas National Forest, Quincy, California
U. S. Forest Service, Sequoia National Forest, Porterville, California
U. S. Forest Service, Sierra National Forest, Northfork, California
U. S. Forest Service, Stanislaus National Forest, Sonora, California
U. S. Forest Service, Tahoe National Forest, Nevada City, California
U. S. Forest Service, Toiyabe National Forest, Reno, Nevada
U. S. Geological Survey, Water Resources Branch, San Francisco, California
U. S. Geological Survey, Water Resources Branch, Tucson, Arizona
Division of Irrigation, U. S. Soil Conservation Service, Reno, Nevada
Kern County Land Company, Bakersfield, California
Los Angeles County Flood Control District, Los Angeles, California
City of Los Angeles, Department of Water and Power, Los Angeles, California
Merced Irrigation District, Merced, California
Metropolitan Water District, Los Angeles, California
Modesto Irrigation District, Modesto, California
Miller and Lux, Los Banos, California
Nevada Agricultural Experiment Station, University of Nevada, Reno, Nevada
Nevada-California Electric Corporation, Riverside, California
Nevada Cooperative Snow-Surveys, 735 West Street, Reno, Nevada
Nevada Irrigation District, Grass Valley, California
Nevada State Engineer's Office, Carson City, Nevada
Pacific Gas and Electric Company, San Francisco, California
Pacific Gas and Electric Company, San Joaquin Power Division, Fresno, California
National Park Service, San Francisco, California
General Grant National Park, General Grant National Park, California
Lassen Volcanic National Park, Mineral, California
Sequoia National Park, Sequoia National Park, California
Yosemite National Park, Yosemite, California
City of San Francisco, Public Utilities Commission, San Francisco, California
Sierra Pacific Power Company, Reno, Nevada
Division of Irrigation, U. S. Soil Conservation Service, Berkeley, California
Southern California Edison Company, Los Angeles, California
Tulare Lake Basin Water Storage District, Hanford, California

South Pacific Coast Area--Concluded

Truckee-Carson Irrigation District, Fallon, Nevada
Turlock Irrigation District, Turlock, California
Washoe County Water Conservation District, Reno, Nevada
U. S. Weather Bureau, Reno, Nevada
U. S. Weather Bureau, San Francisco, California
U. S. Weather Bureau, Phoenix, Arizona

No Specified Area

Dominion Water and Power Bureau, Vancouver, B. C., Canada
Dominion Water and Power Bureau, Ottawa, Canada
U. S. Army Engineers, Washington, D. C.
U. S. Forest Service, Washington, D. C.
U. S. Geological Survey, Washington, D. C.
National Park Service, Washington, D. C.
U. S. Bureau of Reclamation, Washington, D. C.
U. S. Soil Conservation Service, Washington, D. C.
The Shawinigan Water and Power Company, Montreal, Canada
U. S. Weather Bureau, Washington, D. C.

List of persons attending Western Interstate Snow-Survey Conference, Sacramento, California, January 16, 1941

Frank Adams, University of California, Berkeley, California
Olga Austin, Secretary to Fred Paget, Chairman of Executive Committee, Sacramento, California
A. E. Backman, Federal Land Bank, Berkeley, California
W. A. Bertrand, U. S. Weather Bureau, Sacramento, California
Harry F. Blaney, Soil Conservation Service, Los Angeles, California
H. P. Boardman, Nevada Cooperative Snow-Surveys, Reno, Nevada
Harry W. Boetzkes, U. S. Engineer Department, Sacramento, California
John F. Bonner, Pacific Gas and Electric Company, San Francisco, California
P. J. Bosanko, Nevada Irrigation District, Grass Valley, California
Leslie E. Bossen, U. S. Engineer Department, Sacramento, California
E. H. Bowie, U. S. Weather Bureau, San Francisco, California
R. C. Briggs, U. S. Geological Survey, San Francisco, California
J. B. Brown, University of California, Berkeley, California
Lloyd N. Brown, University of California, Berkeley, California
N. M. Cecil, Modesto Irrigation District, Modesto, California
Francis G. Christian, U. S. Engineer Office, Sacramento, California
J. E. Christiansen, University of California, Davis, California
Dr. J. E. Church, Nevada Agricultural Experiment Station, Reno, Nevada
Professor Phil E. Church, University of Washington, Seattle, Washington
Ashton R. Codd, U. S. Weather Bureau, Portland, Oregon
E. A. Colman, U. S. Forest Service, Berkeley, California
Philip S. Cowgill, Sierra Pacific Power Company, Reno, Nevada
Lynn Crandall, U. S. Geological Survey, Idaho Falls, Idaho
Theodore W. Daniel, U. S. Forest Service, Berkeley, California
George G. Devore, Sierra Pacific Power Company, Reno, Nevada
Barry Dibble, Consulting Engineer, Redlands, California
Harry C. Dukes, Federal Water Master, Reno, Nevada
Arthur C. Dunlop, Federal Land Bank, Berkeley, California
N. E. Edlefsen, University of California, Davis, California
Carl Elges, University of Nevada, Reno, Nevada
E. H. Fletcher, U. S. Weather Bureau, Sacramento, California
V. M. Freeman, Santa Clara Water Conservation District, Santa Paula, California
Edwin S. Fuller, Los Angeles County Flood Control District, Los Angeles, California
Anson Gerner, Fresno Irrigation District, Fresno, California
Albert Givan, Sacramento Municipal Utility District, Sacramento, California
C. V. Givan, University of California, Davis, California
Joseph W. Gross, Consulting Engineer, Sacramento, California
L. Standish Hall, East Bay Municipal Utility District, Oakland, California
Ralph C. Hall, Bureau of Entomology and Plant Quarantine, Berkeley, California
E. L. Hamilton, California Forest and Range Experiment Station, Glendora, California
S. T. Harding, University of California, Berkeley, California
George Hardman, Soil Conservation Service, Reno, Nevada
Walter J. Herz, Sierra Pacific Power Company, Reno, Nevada

Horace P. Hinckley, San Bernardino Valley Water Conservation District, Redlands, California
Walter L. Huber, U. S. National Resources Planning Board, San Francisco, California
James E. Jones, Department of Water and Power, Los Angeles, California
L. C. Jopson, Division of Water Resources, Sacramento, California
J. A. Keleher, Nevada Irrigation District, Grass Valley, California
C. J. Kraebel, California Forest and Range Experiment Station, Berkeley, California
William A. Lang, Southern California Edison Company, Ltd., Los Angeles, California
Charles T. Law, Nevada Irrigation District, Grass Valley, California
Charles H. Lee, Consulting Engineer, San Francisco, California
George A. Lewis, Los Angeles Department of Water and Power, Independence, California
T. R. Littlefield, U. S. Forest Service, San Francisco, California
John W. Luce, Los Angeles County Flood Control District, Los Angeles, California
James C. Marr, Soil Conservation Service, Boise, Idaho
Andrew P. Mazurak, University of California Forestry Division, Berkeley, California
E. L. McDonald, East Bay Municipal Utility District, Camp Pardee, Valley Springs, California
George F. McEwen, Scripps Institution of Oceanography, La Jolla, California
Otto H. Meyer, U. S. Engineer Department, Sacramento, California
J. A. Millar, State Engineer Office, Carson City, Nevada
A. T. Mitchelson, Soil Conservation Service, Berkeley, California
Winifred Moore, Secretary to Dr. J. E. Church, Reno, Nevada
Samuel B. Morris, Dean, School of Engineering, Stanford University, California
Dean C. Muckel, Division of Irrigation, Pomona, California
Lee O. Murphy, Pacific Gas and Electric Company, San Francisco, California
Morrough P. O'Brien, University of California, Berkeley, California
Hollis M. Orem, U. S. Geological Survey, Lodi, California
Fred H. Paget, State Division of Water Resources, Sacramento, California
R. L. Parshall, Soil Conservation Service, Fort Collins, Colorado
Walter J. Parsons, Jr., U. S. Engineer Office, Sacramento, California
Joseph B. Paulson, Jr., U. S. Engineer Office, Sacramento, California
Charles W. Petit, Soil Conservation Service, Berkeley, California
H. L. Potts, Board of Water Commissioners, Denver, Colorado
J. J. Prendergast, Bear Valley Mutual Water Company, Redlands, California
F. D. Reyner, Banta Carbona Irrigation District, Tracy, California
Roger Rice, Miller and Lux, Inc., Los Banos, California
R. Robinson Rowe, Department of Public Works, Sacramento, California
Vernon W. Rupp, U. S. Weather Bureau, San Francisco, California
G. H. Russell, Federal Land Bank, Berkeley, California
A. C. Showman, U. S. Engineers, Sacramento, California
T. R. Simpson, Division of Water Resources, Sacramento, California
C. W. Sopp, Pasadena Water Department, Pasadena, California
William Stava, California Railroad Commission, San Francisco, California
P. E. Stephenson, Division of Water Resources, Sacramento, California
R. Earl Storie, University of California, Berkeley, California
Ernest A. Tarr, U. S. Engineers, Sacramento, California
George W. Trauger, Lindsay Strathmore Irrigation District, Lindsay, California
Forrest F. Varney, U. S. Engineer Department, Sacramento, California
F. J. Veihmeyer, University of California, Davis, California
Frank H. Watson, Jr., East Bay Municipal Utility District, Lodi, California
Walter N. Weir, University of California, Berkeley, California
R. A. Work, Soil Conservation Service, Medford, Oregon
A. A. Young, Soil Conservation Service, Pomona, California
Gordon Zander, Division of Water Resources, Sacramento, California

State Division of Water Resources,
Sacramento, California

ERRATA, TRANSACTIONS OF 1940

Part I-B, page 140: Alfred M. Smith, State Engineer, and H. W. Reppert, Assistant State Engineer, of Nevada, both voted for the adoption of the By-Laws and their names should be added under South Pacific Coast Division.

Part I-B, page 142: H. W. Reppert, Assistant State Engineer, Carson City, Nevada, should be added to list of persons attending the Western Interstate Snow-Survey Conference, Stanford, University, January 12, 1940.

Part III-B, pages 832, 835, 1058: Authorship of article beginning on page 835 should be Paul L. Bean instead of Paul L. Bean and Phillip W. Thomas. Corresponding change should be made in "Contents" on page 832 and "Index of names" on page 1058.

INDEX OF AUTHORS, PART I

INDEX OF SUBJECTS, PART I

PUBLICATIONS AND PRICE-LIST TO NON-MEMBERS

Annual meeting	Year	Volume	No. pages	Price, postpaid
1	1920x	None (mimeographed business meeting).	...	....
2	1921	Transactions (Bull. NRC, No. 17).	108	$1.50
3	1922x	None (mimeographed business meeting).	...	....
4	1923	Transactions (Bull. NRC, No. 41).	150	2.00
5	1924x	None (mimeographed business meeting).	...	....
6	1925	Transactions (Bull. NRC, No. 53).	80	1.00
7	1926	Transactions (Bull. NRC, No. 56).	134	1.25
8	1927x	Transactions (Bull. NRC, No. 61).	297	3.00
9	1928	Transactions (Bull. NRC, No. 68).	103	1.00
10-11	1929-30	Transactions (all Sections)	314	1.50
12	1931x	Transactions (all Sections)	229	1.50
13	1932x	Transactions (all Sections)	401	2.00
14	1933x	Transactions (all Sections)	521	2.50
15	1934	Transactions Part I (all Sections except Hydrology) . . .	258	1.25
	1934x	Transactions Part II (Hydrology).	376	1.50
16	1935	Transactions Part I (all Sections except Hydrology) . . .	364	2.00
		Transactions Part II (Hydrology).	166	1.50
17	1936	Transactions Part I (all Sections except Hydrology) . . .	260	1.50
		Transactions Part II (Hydrology and Regional Meetings Hydrology)	204	2.00
18	1937	Transactions Part I (all Sections except Hydrology) . . .	264	1.75
		Transactions Part II (Hydrology and Regional Meetings Hydrology)	300	2.25
19	1938	Transactions Part I (all Sections).	585	3.50
		Transactions Part II (Regional Meetings Hydrology). . . .	180	1.25
20	1939	Transactions Parts I, II, III, IV (all Sections).	741	5.00
		Transactions Part I (Regional Meetings Hydrology)	140	1.25
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		Transactions Part III (all Sections except Hydrology) . .	250	1.75
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22	1941	Transactions Part I (Sacramento Regional Meeting Hydrology)	216	1.50
		Transactions Part II (Washington Annual Meeting, all Sections except Hydrology).	In press	
		Transactions Part III (Washington Annual Meeting, Hydrology)	In press	
Special	(1920)	A survey of research problems in geophysics (Reprint and Circular Series NRC, No. 11)	57	0.60
Special	(1937)	Bibliography of Hydrology, United States of America: Years 1935 and 1936.	78	0.30
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